University of Alberta

PERFORMANCE AND EMISSION CHARACTERISTICS OF CONVERTED VEHICLES RUNNING ON GASOLINE AND NATURAL GAS

By

© **OBIKA CHUKWUDIFU NWOBI**

A Thesis submitted to the Faculty of Graduate Studies and Research in partial Fulfilment of the Requirements for the degree of Master of Science.

Department of Mechanical Engineering

Spring 1994

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The undersigned certify that they have read and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Performance and Emissions Characteristics of Converted Vehicles Running on Gasoline and Natural Gas** submitted by **Obika Chukwudifu Nwobi** in partial fulfilment of the requirements for the degree of **Master of Science**.

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To Nigeria ...

Abstract

Natural gas has been proposed as a viable alternative fuel for spark-ignition engines because of the number of technical and economic advantages it offers. Most natural gas vehicles (NGVs) in operation today are fleet, bi-fuelled trucks that have been converted to run on natural gas or gasoline.

The present study involved the evaluation of the performance and emission characteristics of four GMC Sierra 2500 pickup trucks running on gasoline and natural gas. Three of the trucks had natural gas conversion kits with closed-loop feedback control, while one had a open-loop system - typical of most conversions. The trucks were tested on a drive-shaft dynamometer using a steady-state multi-mode schedule, which was based on FTP-78. They were also run at wide-open throttle to obtain the power/speed and torque/speed curves.

On the average, there was a 5.1 % reduction in fuel consumption and a 19.8 % reduction in carbon dioxide emissions on natural gas. For the trucks with closed-loop controlled conversion kits, the engine-out emissions of oxides of nitrogen, carbon monoxide and reactive non-methane hydrocarbons were down by 35 %, 10.3 % and 81.3 % respectively. The tailpipe emissions however, were higher on natural gas because of reduced catalyst effectiveness. NOx were up by 73.3 %, CO by 13.0 %, and RHC by 73.3 %.

The loss of power on natural gas was less significant at low speeds which are important for truck operation. The average loss of peak power (about 4000 rpm) was 19.2 %, while the loss at 2000 rpm was 13.8 %.

Each of the conversion kits performed well, especially those with closed-loop feedback control. However, the fuel control system of each of the kits still needs to be improved to make them as effective as the state-of-the-art gasoline engines.

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Table of Contents

Page #

Chapter 1: Introduction 1

Chapter 2: Natural Gas for Spark-Ignition 6

2.1: Characteristics of Natural Gas as an S.I. Engine Fuel 6

2.2: Performance and Emission Characteristics of Natural Gas Fuelled Engines 10

2.2.1: Power 11

2.2.2: Carbon Monoxide 12

2.2.3: Hydrocarbons 13

2.2.4: Oxides of Nitrogen 14

2.2.5: Carbon Dioxide 14

2.3: Three-way Catalytic Converters 15

2.4: Studies Of Natural Gas as An Engine Fuel 18

2.4.1: Engine Studies 18

2.4.2: Vehicle Studies 23

2.4.2: NGV Catalyst 24

Chapter 3: Natural Gas Conversion Systems 25

3.1: The Base Trucks 25

3.2: The Conversion Systems Used for the Testing 26

3.2.1: ANGI - Low Emission Vehicle (LEV) System 33

3.2.2: STEWART and STEVENSON/ORTECH - Gaseous Fuel Injection (GFI) System 34

Table of Contents (continued)

Page #

3.2.3: IMPCO/Air Sensors - Alternative Fuel Electronic System 34

3.2.4: VIALLE - Autogas Management System (AMS) 35

3.3: Operation of NGV Control System 35

Chapter 4: Equipment and Procedure 39

4.1: Testing Procedure 40

4.1.1: The Multi-mode Tests Schedule 40

4.1.2: Wide-Open Throttle Tests 45

4.1.3: Testing Equipment and Software 46

4.2: Data Reduction 53

4.2.1: Multi-mode Tests Data Reduction 53

4.2.2: Wide-Open Throttle Tests Data Reduction 63

4.3: Repeatability and Accuracy of Measurement and Calculated Values 65

Chapter 5: Results and Discussion 69

5.1: Multi-mode Test Results 69

5.1.1: Equivalence Ratio 69

5.1.2: Fuel Consumption 75

5.1.3: Carbon Dioxide 78

5.1.4: Oxides of Nitrogen 82

5.1.5: Carbon Monoxide 91

5.1.6: Reactive Non-Methane Hydrocarbons 97

Table of Contents (continued)

Page #

5.1.7: Methane non-Reactive Hydrocarbons 103

5.2: Wide-Open Throttle Tests Results 109

5.2.1: Brake Power 109

5.2.2: Brake Torque 114

5.3: Comparison of the Performance of the Conversion Systems 117

5.3.1: Angi - Low Emission Vehicle (LEV) System 117

5.3.2: Stewart and Stevenson /Ortech -Gaseous Fuel Injection (GFI) 118

5.3.3: Impco / Air Sensors Alternative Electronic (AFE) System 119

5.3.4: Autogas Management System (AMS) 119

Chapter 6: Summary And Conclusions 123

6.1: Summary 123

6.2: Conclusions 127

References 129

Appendices

Appendix A: Multi-mode Composite and WOT Results 132

Appendix B: Raw Experimental Results 147

Lists Of Tables

		Page #
Table 1.1:	World Crude Oil Reserves, Production and consumption	2
Table 2.1:	World Natural Gas Reserves, Production and Consumption	6
Table 2.2:	Properties of Gasoline and Natural Gas Fuels	8
Table 3.1:	Comparison of the Conversion Kits Features	28
Table 3.2:	Comparison of Vehicle Conversion Interfaces (in-Kit)	29
Table 3.3:	Comparison of Vehicle Conversion Interfaces (add-on)	30
Table 3.4:	Qualitatitive Kit Features	31
Table 3.5:	Material Costs of the Base Kits and Accessories	32
Table 3.6:	Installation and Labour Costs	33
Table 4.1:	Representative Natural Gas Composition	40
Table 4.2:	Multi-mode Cycle for GMC Sierra 2500 3/4 ton Truck	41
Table 4.3:	Multi-mode Cycle Summary for GMC Sierra 2500 3/4 ton Truck Ton Truck	42
Table 4.4:	Primary Variable Measured by the Dedicated Program	44
Table 4.5:	Exhaust Emissions with The Gas Chromatograph	45
Table 4.6:	Calibration Gases used for the Testing	50
Table 4.7:	Relative Standard Deviation in Repeat Measurements at a Single Test Point	66
Table 4.8a:	Uncertainty in Mode and Multi-mode Test Results for Gasoline	67
Table 4.8b:	Uncertainty in Mode and Multi-mode Test Results for Natural Gas	68
Table 5.1:	Comparison of the Fuel Consumption and Mixture Control Performance of the four different Conversion Kits	120

Lists Of Tables (continued)

		Page #
Table 5.2:	Comparison of the Engine-out Emissions Performence of the Four Different Conversion Kits	120
Table 5.3:	Comparison of the Tailpipe Emissions Performance of the Four Different Conversion Kits	121
Table 5.4:	Comparison of the Catalyst Conversion Efficiency Performance of the Four Different Conversion Kits.	121
Table 5.5:	Comparison of the Wide-Open Throttle Tests Performance of the Four Different Conversion Kits	122
Table A.1a:	Composite CO_2 and Fuel Consumption Results of Multi-mode Tests on Gasoline	133
Table A.1b:	Composite CO_2 and Fuel Comsumption Results of Multi-mode Tests on Nataural Gas	134
Table A.2a:	Composite Engine-out Emissions Results of Multi-mode Tests on Gasoline	135
Table A.2b:	Composite Engine-out Emissions Results of Multi-mode Tests on Nataural Gas	136
Table A.3a:	Composite Tailpipe Emissions Results of Multi-mode Tests on Gasoline	137
Table A.3b:	Composite Tailpipe Emissions Results of Multi-mode Tests on Natural Gas	138
Table A.4a:	Composite Catalyst Conversion Efficieny Results of Multi-mode Tests on Gasoline	139
Table A.4b:	Composite Catalyst Conversion Efficiency Results of Multi-mode Tests on Natural Gas	140
Table A.5a:	Wide-Open Throttle (WOT) Brake Power Results on Gasoline	141
Table A.5b:	Wide-Open Throttle (WOT) Brake Power Results on Natural Gas	142

Lists Of Tables (continued)

Page #

Table A.6a: Wide-Open Throttle (WOT) Brake Torque Results on Gasoline 143

Table A.6b: Wide-Open Throttle (WOT) Brake Torque Results on Natural Gas 144

Table A.7a: Wide-Open Throttle (WOT) Mean Thermal Efficiency and Equivalence Ratio Results on Gasoline 145

Table A.7b: Wide-Open Throttle (WOT) Mean Thermal Efficiency and Equivalence Ratio Results on Natural Gas 146

List of Figures

		Page #
Figure 2.1:	Variation of Exhaust Emission Components with Equivalence Ratio	11
Figure 2.2:	Variation of Catalyst Conversion Efficiency with Equivalence Ratio	18
Figure 3.1:	Schematic Diagram of a Typical Natural Gas Conversion System	27
Figure 3.2:	Typical ECU Logic Flow for a GFI Kit Control System	36
Figure 4.1:	Exhaust Sample Handling System	47
Figure 4.2:	Loop #1 of Exhaust Gas Analysis System	48
Figure 4.3:	Loop #2 of Exhaust Gas Analysis System	49
Figure 5.1:	Air-Fuel Equivalence Ratio Results with Gasoline and Natural Gas Fuelling at Part-Load (Multi-Modes)	72
Figure 5.2:	Engine-out Oxygen Emission (O_2) Results with Gasoline and Natural Gas Fuelling at Part-Load (Multi-Modes)	73
Figure 5.3:	Comparison of Composite Engine-out (Upstream of Catalyst) Oxygen (O_2) Emissions at Part-Load (Multi-modes)	74
Figure 5.4:	Brake Specific Fuel Consumption (B.S.F.C.) Results with Gasoline and Natural Gas Fuelling at Part-Load (Multi-Modes)	76
Figure 5.5:	Comparison of Composite Fuel Consumption Results at Part-Load (Multi-modes)	77
Figure 5.6:	Engine-out Carbon Dioxide (CO_2) Emission Results with Gasoline and Natural Gas Fuelling at Part-Load (Multi-Modes)	79

List of Figures (continued)

		Page #
Figure 5.7:	Comparison of Composite Engine-out (Upstream of Catalyst) Carbon Dioxide (CO_2) Emissions at Part-Load (Multi-modes)	80
Figure 5.8:	Engine-out Oxides of Nitrogen (NOx) Emission Results with Gasoline and Natural Gas Fuelling at Part-Load (Multi-Modes)	83
Figure 5.9:	Comparison of Composite Engine-out (Upstream of Catalyst) Oxides of Nitrogen (NOx) Emissions at part-Load (Multi-modes)	84
Figure 5.10:	Tailpipe Oxides of Nitrogen (NOx) Emission Results with Gasoline and Natural Gas Fuelling at Part-Load (Multi-Modes)	87
Figure 5.11:	Comparison of Composite tailpipe (Downstream of Catalyst) Oxides of Nitrogen (NOx) Emissions at part-Load (Multi-modes)	88
Figure 5.12:	Comparison of the Composite Oxides of Nitrogen (NOx) Catalyst Conversion Efficiency Part-Load (Multi-modes)	89
Figure 5.13:	Catalytic Converter Temperature Results with Gasoline and Natural Gas Fuelling at Part-Load (Multi-Modes)	90
Figure 5.14:	Engine-out Carbon Monoxide (CO) Emission Results with Gasoline and Natural Gas Fuelling at Part-Load (Multi-Modes)	92
Figure 5.15:	Comparison of Composite Engine-out (Upstream of Catalyst) Carbon Monoxide (CO) Emissions at part-Load (Multi-modes)	93
Figure 5.16:	Tailpipe Carbon Monoxide (CO) Emission Results with Gasoline and Natural Gas Fuelling at Part-Load (Multi-Modes)	95

List of Figures (continued)

Page #

Figure 5.17: Comparison of Composite Tailpipe (Downstream of Catalyst) Carbon Monoxide (CO) Emissions 96

Figure 5.18: Engine-out Reactive Non-Methane Hydrocarbons (RHC) Emission Results with Gasoline and Natural Gas Fuelling at Part-Load (Multi-Modes) 98

Figure 5.19: Comparison of Composite Engine-out (Upstream of Catalyst) Reactive Non-Methane Hydrocarbons (RHC) Emissions at part-Load (Multi-modes) 99

Figure 5.20: Tailpipe Reactive Non-Methane Hydrocarbons (RHC) Emission Results with Gasoline and Natural Gas Fuelling at Part-Load (Multi-Modes) 101

Figure 5.21: Comparison of Composite Tailpipe (Downstream of Catalyst) Reactive Non-Methane Hydrocarbons (RHC) Emissions at part-Load (Multi-modes) 102

Figure 5.22: Engine-out Methane Hydrocarbons (CH_4) Emission Results with Gasoline and Natural Gas Fuelling at Part-Load (Multi-Modes) 104

Figure 5.23: Comparison of Composite Engine-out (Upstream of Catalyst) Methane Hydrocarbons (CH_4) Emissions at part-Load (Multi-modes) 105

Figure 5.24: Tailpipe Methane Hydrocarbons (CH_4) Emission Results with Gasoline and Natural Gas Fuelling at Part-Load (Multi-Modes) 107

Figure 5.25: Comparison of Composite Tailpipe (Upstream of Catalyst) Methane Hydrocarbons (CH_4) Emissions at part-Load (Multi-modes) 108

Figure 5.26: Corrected Brake Power Results with Gasoline and Natural Gas Fuelling at Wide-Open Throttleas a Function of Engine Speed at WOT 110

List of Figures (continued)

		Page #
Figure 5.27:	Comparison of the Peak Brake Power Values at Wide-Open Throttle	111
Figure 5.28:	Corrected Brake Torque Results with Gasoline and Natural Gas Fuelling at Wide-Open Throttleas a Function of Engine Speed at WOT	115
Figure 5.29:	Comparison of the Peak Brake Torque Values at Wide-Open Throttle	116

CHAPTER 1

INTRODUCTION

Since their development, automotive internal combustion engines have used refined petroleum-based fuels which possess the required combustion properties. Gasoline and diesel fuels have been used as the main spark-ignition and compression-ignition engine fuels respectively, and the engines are usually optimized for these fuels. Generally, the progress of internal combustion engines has closely paralleled the development of the petroleum industry [1]. However, over the past few years, extensive studies have been performed on alternative fuels such as the alcohols (methanol, ethanol and butanol), compressed natural gas (CNG), liquefied petroleum gas (LPG), and hydrogen. This emphasis on alternative fuels is mainly due to the energy conservation and security concerns, and the increasingly stringent emission limits for engines in an attempt to improve air quality.

Based on the 1990 statistics, the world's total proven crude oil reserve is about 136,500 million tonnes while the total annual consumption is about 3,102 million tonnes [2]. From these estimates, the world's oil reserves are expected to last for about 43 years. Though new reserves are being discovered, at the present level of consumption, there is no doubt that the conventional oil reserves will decline and become depleted within the next two centuries. Hence the continued utilization of internal combustion (I.C.) engines will depend on the efficient transition to one or more alternative fuels. Table 1.1 shows the world's oil reserves, as well as the annual consumption and production rates.

Table 1.1: World Crude Oil Reserves, Production and Consumption (1990 Estimates)[2]

Region of World	**Reserves** (Million Tonnes)	**Production** (Million Tonnes)	**Consumption** (Million Tonnes)	**Years of Reserves Remaining**
USA Canada N/America	4,300 1,000 5,300	417.6 93.3 510.9	778.9 74.8 853.7	10.4
Latin America	17,100	373.7	254.8	45.8
Western Europe	1,900	201.9	617.8	9.4
USSR + C/Europe	8,100	584.9	482.0	13.9
Middle East	89,500	843.3	146.3	106.1
Africa	7,900	313.5	93.9	25.2
Asia + Australasia	6,700	320.7	650.2	20.9
TOTAL WORLD	**136,500**	**3148.9**[1]	**3101.4**[1]	**43.3**

[1] Differences between world production and consumption are accounted for by stock changes, statistical differences and oil "Destination not Known"

Automotive engines are a major source of pollution in cities and there is a need to improve the air quality in order to reduce global warming, acid rain, photochemical smog, etc, with the associated health and environmental hazards. Although alternative fuels are not a panacea for air quality problems, they may make possible, in conjunction with other emissions control measures, reduction in automotive pollutant emissions. Some alternative fuels are also known to possess some favourable physical and chemical properties which could lead to better vehicle and fuel performance.

Natural gas has been proposed as the most viable alternative spark-ignition engine fuel due to its several inherent advantages [1, 3-8]. These include low pollutant emissions, low cost, availability and ease of distribution using the existing pipeline networks, and easy adaptability to current gasoline engines. The big advantage of replacing some percentage of the petroleum fuels with natural gas is somewhat counter-balanced for the moment by the low level of development of the technology for this application. At the moment there is no large network of fuelling stations. To develop that infrastructure, a generation of bi-fuel natural gas conversions is required.

It is often necessary to convert existing gasoline-fuelled engines for compressed natural gas (CNG) operation since only a relatively small number of natural gas engines are available from vehicle manufacturers. There are over 26,000 natural gas vehicles (NGVs) in operation in Canada; 700,000 around the world [6] and most of these NGVs are fleet trucks converted to run on either gasoline or natural gas. It is hoped that the growing number of converted vehicles will produce the fuel demand that will justify the development of natural gas compression stations, lightweight fuel cylinder production facilities and other necessary elements of the overall fuel infrastructure. This might lead to an eventual replacement of the fleet with dedicated technology and the use of natural gas as a vehicle fuel on a larger scale. Hence, in the immediate future, research should be concentrated on the development of actual, commercial conversion kits and the quantification of the performance, economics, and environmental impact of those conversions on fleet trucks.

Many studies have been carried out on natural gas as a spark-ignition engine fuel (see review in chapter 2). However, most researchers have either concentrated on testing only engines/vehicles optimized for natural gas operation, or have tested only engines, instead of using full vehicles to ensure that all sensors, actuators, control strategies, and other factors are active during testing. Some other studies have used driving schedules that do not exercise the engines/vehicles over the range of conditions representative of actual use.

The objective of the present study was to evaluate the performance characteristics of four converted GMC Sierra 2500 pickup trucks. The trucks had new 5.7 litre engines and new natural gas conversion kits. Each truck was to be tested on both gasoline and natural gas and the overall performance quantified in terms of engine performance, emissions characteristics, catalytic converter performance, and fuel economy. Four different conversion kits (Angi, GFI, Impco, and Vialle) were used in the study and each of the trucks had a different kit. Three of the kits had closed-loop feedback control systems, while one had an open-loop system. Full-sized pick-up trucks were chosen because they are common targets for conversion to natural gas operation.

The trucks were tested on a chassis drive-shaft dynamometer in the engine laboratory at the Department of Mechanical Engineering, University of Alberta. Each vehicle was tested using the multi-mode test schedule (part-load) that included a cold-start followed by steady-state operation in 15 different speed/load modes to measure the fuel consumption, emissions (engine-out and tailpipe), and the catalytic converter performance. The test schedule was based on the combined Environmental Protection Agency (EPA) City and Highway Test Schedules, that is the Federal Testing Procedure of 1978 (FTP-78). This schedule exercised each vehicle over a range of conditions representative of actual use. Each truck was also run at wide-open-throttle to produce the maximum power and torque curves, and the fuel consumption.

Chapter 2 gives an overview of the background information. It briefly summarizes the characteristics and use of natural gas as a vehicle fuel. It also deals with the performance, exhaust emissions and control of natural gas-fuelled engines and then gives a brief literature review of past studies done in the area. The natural gas conversion systems used in the tests and the general NGV control systems are discussed in chapter 3. Chapter 4 describes the test equipment and procedure and the error analysis, while the results and discussions are presented in chapter 5. Chapter 6 gives the summary and conclusions obtained from the present study. Raw experimental and processed results are included in the appendix.

CHAPTER 2

NATURAL GAS FOR SPARK-IGNITION ENGINES

2.1 CHARACTERISTICS OF NATURAL GAS A SPARK- IGNITION ENGINE FUEL

The use of natural gas as a viable spark-ignition (S.I.) engine fuel is becoming a reality as the number of natural gas vehicles in operation world-wide is about three-quarters of a million. This emerging trend of natural gas as a pragmatic alternative fuel for S.I. engines is due to the number of technical and economic advantages it offers.

Natural gas is widely available with an estimated reserve of about 119.4 Tcm and an annual consumption of only 1.93 Tcm [2]. Table 2.1 shows the world's natural gas reserves, as well as the annual consumption and production rates.

Table 2.1: World Natural Gas Reserves, Production and Consumption (1990 Est.) [2]

Regions of the World	**Reserve**[1] (10^{-3} Tcm)	**Production** (10^{-3} Tcm)	**Consumption** (10^{-3} Tcm)	**Years Remaining**
USA	4,700	493.1	545.0	
Canada	2,800	97.8	61.1	
North America	7,500	590.8	606.1	12.7
Latin America	7,000	90.44	87.7	77.4
Western Europe	5,000	175.2	247.8	28.5
USSR + Central Europe	45,800	771.4	707.2	59.4
Middle East	37,600	103.5	99.6	363.3
Africa	8,100	67.3	36.6	120.4
Asia +Australasia	8,400	158.5	146.3	53.0
TOTAL WORLD	**119,400**	**1957.1**[2]	**1930.0**	**61**

[1] Tcm is trillion cubic meters.

[2] Differences between world production and consumption are accounted for by stock changes, statistical differences and oil shipment "Destination not Known"

Based on the 1990 estimates, the number of years remaining for the natural gas reserves is about 61, while that for gasoline is about 43. However, natural gas reserves have risen steadily for the past 25 years and the resource is expandable as it can be obtained from a variety of unconventional resources such as sewage and biomass, shale oil, coal-bed gasification, and solar resources. The vast natural gas pipeline systems already in place in such areas as North America and Europe make the distribution of the fuel both economical and reliable.

Current gasoline-fuelled engines can be readily adapted to use natural gas with only minor modifications. The conversion normally involves the incorporation of a gas system which includes the fuel cylinder, fuel line, pressure regulators, carburation equipment, and electronic controls. Normally, the engine is not modified internally in order to maintain gasoline capability.

Table 2.2 gives a comparison of the properties of gasoline and natural gas as engine fuels. From the table, it is seen that natural gas with octane rating of 105-122, has better anti-knock qualities than gasoline which has octane rating of 87-92. Hence, natural gas-fuelled engines can safely use compression ratios as high as 15:1 (compared to 8-10:1 for gasoline-fuelled engines). Higher compression ratio results in increased power output and higher thermal efficiency. Moreover, because of the high knock-limited compression ratio, harmful fuel additives such as lead are not required.

Table 2.2: Properties of Gasoline and Natural Gas Fuels [3,9]

PROPERTIES	GASOLINE	NATURAL GAS
Phase at ambient conditions	liquid	gas
Stoichiometric A/F ratio (mass basis)	approx. 14.6	approx. 16.8
Lower heating value Mass (MJ/kg) Volume (MJ/l)	 43.5 32	 47.4 8.0[1]
Composition	mostly C_4 to C_{12} hydrocarbons	about 85-96 % methane, rest other gases
Octane rating (R+ M)/2	87-92	105-122
Flame speed in air at stoichiometric (m/s)	approx. 0.390	approx. 0.375
Lean flammability equivalence ratio	about 0.66	about 0.52
Ignition temperature (° C)	260	650
Specific gravity (@15 °C, 1 bar)	0.72-0.76	0.00079
Boiling point (° C)	30-225	-162
Molecular weight	about 110	about 18.7
Cost (cents/l) [2]	55	24

[1] on an energy equivalent comparison (at Edmonton stations, May, 1993)

[2] in storage conditions (15°C, 220 bar)

It is generally believed that natural gas is an environmentally friendly transportation fuel. The combustion of natural gas in engines causes considerably less hydrocarbon pollution with low photochemical reactivity, zero evaporative emissions and reduced emissions of carbon dioxide (a "greenhouse" gas), than gasoline. The use of natural gas could, therefore, help to improve air quality relative to conventional liquid fuels. The problem of automotive pollution does not simply rest with air contamination. Pollution of water supplies through leaking storage tanks or spillage is a serious environmental hazard. Unlike liquid fuels such as gasoline, diesel or methanol, natural gas does not contaminate ground water. Moreover, less energy and, hence, less pollution is involved in the production and refining of natural gas.

Methane, the main component of natural gas, is non-toxic, non-corrosive and non-reactive in the atmosphere, and the operational characteristics of the gas make it an inherently safer fuel than gasoline. The higher ignition temperature, limited flammability range and light weight make accidental ignition or combustion of the gas unlikely. For use in vehicles, natural gas is normally compressed and stored in high-pressure cylinders which are built to much more rigorous standards than gasoline or propane tanks. These systems are appreciably safer than gasoline systems in accident situations and impact tests [5].

The major disadvantage of natural gas as a vehicle fuel, compared with gasoline, is reduced range. This limitation in range is due to the low "energy density" of the gas (8.0 versus 32 MJ/l at 15 °C, 220 bar). Also, the additional weight, bulk and cost of natural gas cylinders compared to conventional fuel tanks, constitute drawbacks in many types of service. Moreover, since the gas cylinders are normally pressurized, there is an additional hazard of pressurized leaks. However, this range disadvantage is least significant for large vehicles which have enough space and weight capacity.

2.2 PERFORMANCE AND EMISSIONS CHARACTERISTICS OF NATURAL GAS FUELLED-ENGINES

Engine operating range is limited by emission regulations which require the use of three-way catalytic converters to produce acceptable emission levels. The importance of these converters is more significant in larger vehicles since emission levels are measured in grams per mile (or grams per kilometre) and, so, larger vehicles which use more fuel cannot meet the required levels as easily as the smaller ones. These converters simultaneously oxidize carbon monoxide (CO) to carbon dioxide (CO_2), and hydrocarbons (HC) to carbon dioxide (CO_2) and water (H_2O), and reduce oxides of nitrogen (NOx) to nitrogen (N_2) and oxygen (O_2). In order to improve performance and reduce catalyst-out emissions, spark-ignited internal combustion engines are typically operated within 1 % of stoichiometric air-fuel ratio and held to this limit by a closed-loop electronic control strategy using an exhaust oxygen sensor. The control system should be capable of reacting to the rapid changes in speed and load typical of automotive service.

Figure 2.1 shows typical plots of the variation of the exhaust emission components (NOx, CO and HC) with air-fuel equivalence ratio [10]. It is evident from figure 2.1, that the cumulative sum of the three major pollutants is low for stoichiometric mixtures. As the mixture goes rich, hydrocarbons and carbon monoxide emissions increase, while the maximum oxides of nitrogen level occurs at slightly lean air-fuel ratios. In fact, precise control of the air-fuel ratio around stoichiometric is required in order to obtain the best combination of fuel economy, power, and emission.

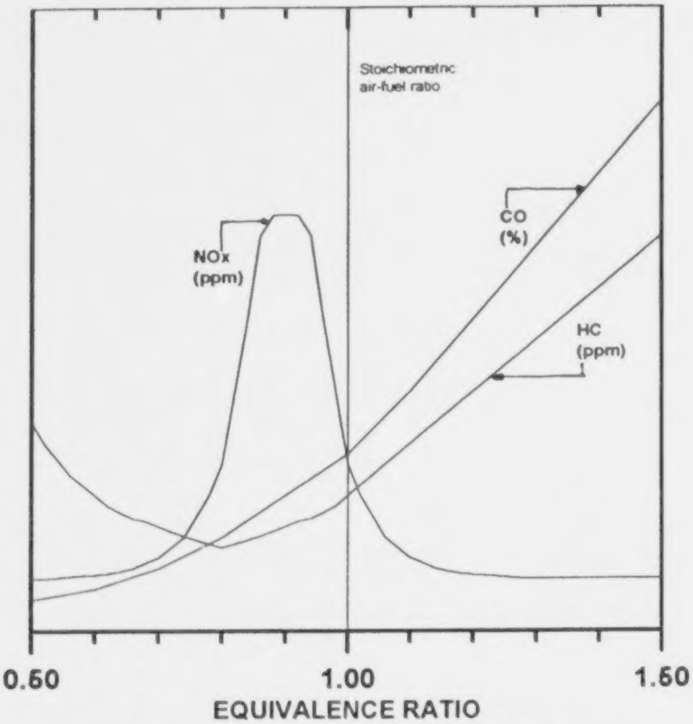

Figure 2.1: Variation of Engine-out Emissions Concentration with Air-Fuel Equivalence Ratio [10]

2.2.1 Power

Gasoline engines converted to run on natural gas are known to produce up to 16 % less power at full throttle than on gasoline [10-14]. Segal and Keffer [15] showed power losses of up to 22.1 % on natural gas. This power loss is caused by the absence of evaporative charge cooling, loss of volumetric efficiency (10 % of the air is displaced by the gaseous fuel), slower burning speed of natural gas, and to a lesser extent, the presence of such inert gases as nitrogen and carbon dioxide in the fuel. It could also be caused by the effect of the gas mixer on inlet air flow. Though the power loss can be minimized by increasing the compression ratio and by using more spark advance in optimized natural gas engines, bi-fuel conversions still require gasoline compatibility, such that the power loss remains and must, therefore, be considered.

2.2.2 Carbon Monoxide (CO)

The most important engine parameter influencing carbon monoxide emissions is the air-fuel equivalence ratio. CO is produced when the engine is running rich because of the insufficient amount of oxygen available to convert all the carbon to carbon dioxide (CO_2). Also, for stoichiometric or lean mixtures, the CO emission is not equal to zero because of cycle to cycle and cylinder to cylinder fuel variations, and the slow CO dissociation kinetics. Additional sources of CO appears to be caused by the flame-fuel interaction with the walls, the oil films, and the deposits on the combustion chamber walls. Generally, the use of natural gas in spark-ignition engines leads to the production of lower engine-out CO emissions than gasoline, for operations at the same air-fuel equivalence ratio [9, 13, 14, 16, 17]. This is due to the gaseous nature of natural gas which ensures adequate mixing of the fuel and air, and the elimination of cold-start enrichment. Moreover, because of its low carbon-to-hydrogen ratio, natural gas engines have inherently lower engine-out emissions of CO.

2.2.3 Hydrocarbons (HC)

The engine-out hydrocarbons emissions are dependent on the air/fuel ratio and the ignition timing. For rich mixtures, there is simply more fuel available than can be burned with the available oxygen so that the emissions increase with the richness of the mixture. With retarded timing, the process of combustion is not completed in the cylinder before the exhaust valves open. Consequently, the combustion process continues in the exhaust system where the remaining hydrocarbons are burned up.

When operated very close to the stoichiometric air-fuel ratio, natural gas-fuelled engines are known to produce lower non-methane reactive hydrocarbons (RHC) than those fuelled with gasoline [9, 14, 17]. This is due to the fact that methane (CH_4) is the dominant constituent of natural gas, and since an appreciable proportion of the exhaust hydrocarbons are composed of completely unreacted fuel, methane hydrocarbons (CH_4) dominate the total hydrocarbons (THC) emissions from natural gas vehicles (NGVs). The THC emissions from natural gas engines, on the other hand, tend to be fairly high because of the slow reactivity of methane. While the NGV hydrocarbon emissions dominated by CH_4 is advantageous from the perspective of the "Clean Air Act" which enforces standards on non-methane hydrocarbons, the relative high emission rate of methane poses some concern over the "greenhouse" effect. However, tests conducted by Tsao et al. [16] showed that gasoline engines converted to run on natural gas can produce higher total hydrocarbons emissions on the gaseous fuel.

2.2.4 Oxides of Nitrogen (NOx)

Natural gas-fuelled engines are known to give lower engine-out oxides of nitrogen (mainly NO and NO_2) emissions than gasoline fuelled ones [9, 13, 16]. The higher NOx from gasoline is due primarily to the lower combustion temperatures with natural gas (for stoichiometric mixtures in air at standard temperature and pressure (STP), the flame temperature of methane is about 1875 °C compared to 2300 °C for gasoline) [13]. However, in situations where advanced spark timing or higher compression ratios are required for natural gas fuel operation, it is possible for an engine to generate higher NOx levels on the gaseous fuel than on gasoline [9]. Tests conducted by Fleming and O'Neal [14] showed higher NOx emissions on natural gas.

Engine-out NOx emissions can be further controlled by exhaust gas recirculation (EGR), and natural gas engines can tolerate higher EGR rates than gasoline engines [3]. The recycled exhaust gas acts as a diluent, and this reduces the peak flame temperature.

2.2.5 Carbon Dioxide (CO_2)

The concern about global warming due to the accumulation of carbon dioxide in the atmosphere provides another advantage for the use of natural gas as an engine fuel. For the same energy output, natural gas fuelled engines could produce up to 20 % less CO_2 than those fuelled with gasoline [17]. This could be primarily due to the higher hydrogen to carbon ratio for the gaseous fuel, and to the lower fuel consumption on natural gas:

CH_4 has about 11 % greater LHV than octane (by mass)

CH_4 contains 75 % carbon (by mass)

C_8H_{18} contains 84 % carbon (by mass)

This gives a ratio of

$$0.84/0.75=1.12 \tag{2.1}$$

For the same energy, we expect to use the following percentage of carbon from natural gas

$$(1/1.12)\times(1/1.11)=80\% \tag{2.2}$$

Hence the CO_2 formed from natural gas is about 80 % of that formed from gasoline.

2.3 THREE-WAY CATALYTIC CONVERTERS (TWC)

Three-way catalytic converters are often used to reduce the exhaust emissions as spark-ignition engines produce pollutant emissions in excess of the current standards. Whereas a 2000 kg vehicle may emit about 2 to 3 g/mile hydrocarbons, 20 to 30 g /mile carbon monoxide (CO) and 1 to 1.5 g/mile oxides of nitrogen (NOx), the current standards for cars are 0.41 g/mile for hydrocarbons, 3.4 g/mile for carbon monoxide, and 1.0 g/mile for oxides of nitrogen [18]. These converters eliminate pollutants by the simultaneous oxidation of carbon monoxide and hydrocarbons, and the reduction of oxides of nitrogen. The oxidizing agents are mainly oxygen and the oxides of nitrogen, while the reducing species are the hydrocarbons and carbon monoxide.

Oxidation of Hydrocarbons

Hydrocarbons are oxidized to carbon dioxide and water by the oxidizing agents in the raw exhaust; excess oxygen and oxides of nitrogen. The oxidation reactions are given by equations 2.3 and 2.4, respectively.

$$C_xH_y+(x+\frac{y}{4})O_2\rightarrow xCO_2+\frac{y}{2}H_2O \tag{2.3}$$

$$C_xH_y+(2x+\frac{y}{2})NO\rightarrow xCO_2+(x+\frac{y}{4})N_2+(\frac{y}{2})H_2O \tag{2.4}$$

Since methane, the main constituent of the total hydrocarbons emissions from natural gas-fuelled engines has a very low reactivity [3], it is not easily oxidized by the catalyst. Hence the hydrocarbons conversion efficiencies in these engines are often lower than those of the gasoline-fuelled engines. However, since methane is non-toxic and does not contribute to ozone formation, the low conversion efficiency is not a matter of concern at the moment.

Oxidation Of Carbon Monoxide

Carbon monoxide is oxidized by the oxides of nitrogen and excess oxygen in the exhaust. The CO oxidation reactions are illustrated by equations 2.5 and 2.6:

$$2CO+O_2 \rightarrow 2CO_2 \qquad (2.5)$$

$$CO+NO \rightarrow CO_2+\frac{1}{2}N_2 \qquad (2.6)$$

Reduction of Oxides of Nitrogen

Oxides of nitrogen are reduced to nitrogen by the hydrocarbons and carbon monoxide. The NOx reduction processes are illustrated in equations 2.4 and 2.6. However, NOx catalytic conversion in natural gas engines are less effective and requires a richer mixture than gasoline engines [3]. The likely reason for this difference is the lower concentration of CO and reactive hydrocarbons in the raw exhaust of natural gas engines.

The most critical factor in TWC systems is the control of the air-fuel mixture in a narrow window about the stoichiometric. Conversion efficiencies for hydrocarbons and carbon monoxide are lost very rapidly as richer mixtures are reached, while NOx efficiency declines almost precipitously as the mixture gets lean. Figure 2.2 shows the effect of air-fuel equivalence ratio on the conversion efficiencies of a three-way catalyst.

Hence, precise control of air-fuel ratios using a closed-loop control is essential for the successful attainment of future emission standards for NGVs. The control system should have the ability to respond quickly and accurately to maintain the air-fuel ratio within the narrow window.

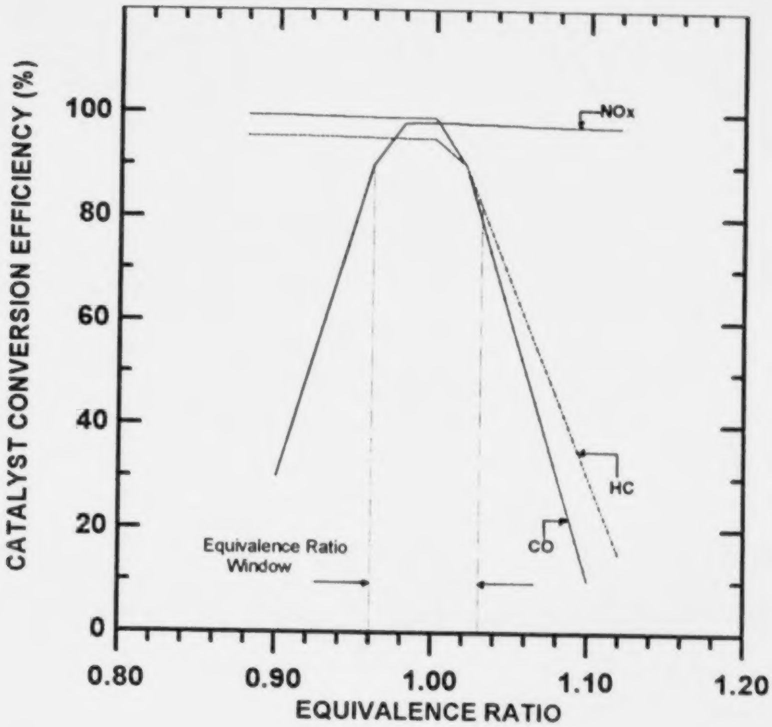

Figure 2.2: Variation of Catalyst Conversion Efficiencies with Equivalence Ratio [3]

2.4 STUDIES OF NATURAL GAS AS AN ENGINE FUEL

Most spark-ignition engines and vehicles converted to run on natural gas use a stoichiometric mixture. In the last few years investigations have been directed at fuelling systems for spark-ignition engines, engine controls, and catalytic controls of pollutants emitted by natural gas engines.

2.4.1 Engine Studies

Segal and Keffer [15] tested engines converted to run on natural gas in order to evaluate the results of conversion to natural gas fuel. They also compared the available natural gas carburation systems. The first test was carried out on a representative light-duty engine, a Ford 4.9 L engine, with four different available natural gas carburation systems. The second test used an engine representative of heavy-duty engines, Ford 6.1 L LIMA, with three available designs of carburation systems [19]. The systems had no feedback control. The tests were performed on an engine dynamometer, with the power at wide-open-throttle (WOT), and the brake specific fuel consumption and emissions at different fixed speeds and loads being monitored and compared with baseline tests on gasoline.

In the first test, the power loss on natural gas compared to gasoline was found to range between 12.3 and 22.1 %. The best natural gas conversion system tested showed between 6.4 % improvement and 9.8 % reduction in energy efficiency. The total hydrocarbons (expressed as methane) were found to be higher on natural gas, while the oxides of nitrogen and carbon monoxide emissions were found to be comparable for both fuels. In the second test, the power loss ranged between 6.1 and 15.2 % on natural gas (compared to gasoline), while the energy efficiency varied between 33.6 % higher and 11.9 % lower on natural gas. The hydrocarbons and carbon monoxide emissions were generally lower on natural gas, while at some operating points, the oxides of nitrogen were higher.

Bell et al. [11] performed tests on a 1987 GM 4-cylinder, 2.5 L spark-ignited engine. They acquired baseline performance data for gasoline and natural gas fuelling at several operating conditions (specified throttle and speed settings: at 100 %, 75 %, 50 %

and 25 % WOT, and at 1600 rpm to 3200 rpm at 200 rpm intervals). Among other parameters, the brake power and the brake specific fuel consumption for the two fuel operations were compared. Their studies showed that natural gas fuelling decreased power by about 13 % at low throttle and about 16 % at higher throttle setting.

Varde et al. [9] evaluated the exhaust emissions characteristics, the catalyst effectiveness, and the performance of two S.I. engines running on gasoline and natural gas. The engines were a 4-cylinder, 1.6 L; and a 1-cylinder, 0.4 L converted with mechanical natural gas carburation systems and fitted with 2-way and 3-way catalyst. The tests were conducted on a water brake type dynamometer and were carried out at steady state conditions at 20 %, 40 %, 60 % and 90 % of full load. The loss of power on natural gas ranged between 9 and 14%, while the oxides of nitrogen emissions reduction ranged between 36 % at low loads to about 17 % at full load. The carbon monoxide emissions on natural gas were about 50 % of those found on gasoline. Though the total hydrocarbons emissions for both fuels were comparable, the proportion of methane in the natural gas operation was as high as 50 % for some operating points while it was less than 2 % on gasoline.

Jaaskelainen and Wallace [13] studied the emission characteristics and performance of a two-litre, four-cylinder Nissan SR20DE engine representative of modern design practice. The engine was operated on gasoline and natural gas at six different loads and three different speeds. A feedback-controlled carburation system was used with the natural gas fuelling to maintain stoichiometric operation. At each point, exhaust emissions were measured, while at selected points, the effects of air-fuel ratio, spark timing and EGR were investigated. Decrease in maximum torque of up to 15 % resulted from natural gas fuelling, while all the regulated exhaust emission components were also reduced on natural gas.

Evans et al. [12] made an experimental evaluation of the power output, specific fuel consumption and thermal efficiency of a 4-cylinder spark-ignition engine operating on gasoline and natural gas. Tests were conducted at various speeds, spark advance angles and air-fuel ratios, all at wide-open-throttle, on a water-brake dynamometer. The brake power, brake torque and brake mean effective pressure were corrected using the SAE Power Test Code, J1349. However, the engines had no feedback control of the air-fuel ratio. With natural gas operation, brake power was found to decrease by between 11.3 and 16 % compared to gasoline operation, while the brake specific consumption was found to decrease with natural gas operation.

Sierens [20] carried out comparative tests on a commercial diesel engine (Valmet, 420D, 4-cylinder) converted to run on natural gas or hydrogen. The influences of air-fuel ratio and ignition timing on power, torque, fuel consumption, exhaust gas components, and effective efficiency were evaluated. The study neither evaluated the performance of state-of-the-art conversion kits, nor was the engine operated at stoichiometric air-fuel ratio. Moreover, the performance of the engine on the alternative fuels could not be compared to the performance on gasoline.

Fleming and O'Neal [14] carried out experimental work on a single-cylinder Labeco Coordinating Lubricant (CLR) engine, chosen to be a representation of the average light-duty vehicle engine. Data on thermal efficiency and emissions from natural gas tests at optimized compression and air-fuel ratios were compared with similar data from gasoline and natural gas baseline compression ratio of 8.4:1. For the baseline compression ratio, indicated thermal efficiency (or fuel consumption), total hydrocarbon and carbon monoxide emissions were similar for natural gas and gasoline operations, while the oxides of nitrogen emissions were slightly higher on natural gas. However, increasing the compression ratio increased the thermal efficiency and the total hydrocarbons emissions on natural gas.

2.4.2 Vehicle Studies

Though these studies were useful in comparing results from the baseline tests on gasoline and the converted natural gas settings, and between the various conversion kits for the case of Segal and Keffer, in controlled laboratory conditions, caution has to be exerted in translating the results to real-world situations. Firstly, since full vehicles were not used for the tests, the effects of the sensors, actuators, control strategies and other factors that affect the performance of vehicles during real driving were not monitored. Secondly, the driving schedules used did not exercise the engine over the same range of speeds and loads as the FTP-78. In other words, the engines were not all exercised over a range of conditions that are representative of actual use.

An investigation on the performance and emission characteristics of natural gas-fuelled vehicles have also been carried out. Tsao et al. [16] evaluated the emission characteristics and the catalyst effectiveness of a fleet of five bi-fuelled trucks (7.0 L V8 engines) running on either gasoline or natural gas. The tests were conducted on a chassis dynamometer using a test procedure of 14 operating modes formulated based on EPA codes. However, the power produced by the engine and the fuel consumption rate were not evaluated. Moreover, the effect of power, air-fuel ratio, and equivalence ratio on the engine-out and tailpipe emissions, and catalytic converter effectiveness were not considered. In most cases, the carbon monoxide and oxides of nitrogen emissions were found to be lower on natural gas, while the total hydrocarbons were found to be higher.

The development of dedicated NGV technology is the main objective of many studies. This has resulted in the organization of three NGV Challenge competitions among engineering schools in North America. The competition [21] required that student engineers convert a production 1991 GMC Sierra 2500 to dedicated natural gas operation. The challenge involved the optimization of the vehicles for natural gas operation and thus did not require the more relevant option of bi-fuel operation. In order to accomplish these goals, several modifications were made. Some schools increased the compression ratio of the engine, while others used gaseous fuel injection systems over carburation systems. For the 1992 NGV challenge [22], the program continued to spur development and demonstrate technologies for advanced dedicated natural gas spark-ignited engines.

2.4.3 NGV Catalysts

Several studies have been done on advanced NGV catalyst formulations for long-term performance and durability. White [23] carried out a durability study of eight catalytic converters specially designed for natural gas operation. The converters were aged for 300 hours on a natural gas fuelled 7.0 L Chevrolet engine operated at net stoichiometric conditions. The converter performance was evaluated using both engine and FTP vehicle tests. The study showed that the air-fuel ratio for effective, simultaneous conversion of total hydrocarbons, carbon monoxide, and oxides of nitrogen is more narrow for natural gas-fuelled engines than for gasoline-fuelled engines. However, the test was done using converters that are optimized for natural gas operations, instead of the prevailing situation for conversion vehicles with converters that are optimized for gasoline operation .

CHAPTER 3

NATURAL GAS CONVERSION SYSTEMS

3.1 THE BASE TRUCKS

The four trucks used for the study were selected to be representative of light-duty fleet trucks which are the target for natural gas conversion. All four vehicles used in the study were GMC Sierra 2500 trucks equipped with the KL-5 "conversion" engine option.

Vehicle Specifications [24]

Model
GMC Sierra 2500 series (3/4 ton truck)

Type
Long box 2.4 m (8 ft.)
Regular cab (three-passenger,two-door)
Front engine/rear wheel drive

Specifications
Length: 5400 mm (212.6")
Wheelbase: 3340 mm (131.5")
Tire radius: 346 mm
Axle ratio: 4.1

Engine
5.7 L V8 "gaseous fuel compatible"
(Designed by GM to operate on propane, natural gas or gasoline)
8.1 compression ratio
170 HP (126.8 kW) at 4000 rpm

Features
4-speed automatic transmission with overdrive
All-season, steel-belted radial tires
Rear-wheel, anti-lock Brakes

3.2 THE CONVERSION SYSTEMS

The natural gas conversion kits used in the study ranged from a conventional mixer, another mixer with feedback control to a fully strategized, pulse-width-modulated gas injection system [25]. A typical conversion kit normally includes fuel cylinders, fuel lines, regulators (low and high pressure regulators), carburation equipment (carburettors, mixers and fuel injectors), and electronic controls (electronic control unit, sensors, actuators, etc). Fig 3.1 shows a schematic diagram of a typical conversion system. Typically, the compressed natural gas (CNG) is stored at high pressures of about 3000 psi in high-pressure steel or aluminum tanks installed in the rear or undercarriage of the vehicle. The conversion could involve the modification of the air cleaner housing and the crankcase vent to incorporate the carburation equipment. When fuel is required by the engine, the natural gas leaves the tanks and flows through the fuel lines and the regulators which reduce the pressure to the levels required by the fuel metering device. This device draws proportionate amounts of fuel and air in order to maintain stoichiometric mixtures.

The natural gas conversion kits used for the study were:

1. Angi - Low Emission Vehicle System (LEV) installed in truck #1 (red truck)
2. Stewart and Stevenson/Ortech - Gaseous Fuel Injection System (GFI) installed in truck #2 (dark-blue Truck).
3. Impco/Air Sensors - Alternative Fuel Electronics System (AFE) installed in truck #3 (light-blue truck).
4. Vialle - Autogas Management System (AMS) installed in truck #4 (silver truck).

Table 3.1 presents a comparison of the features of the conversion kits while the in-kit and add-on vehicle interfaces are shown in tables 3.2 and 3.3, respectively. Table 3.4 shows a comparison of the qualitative kit features while tables 3.5 and 3.6 show the material costs and installation costs, respectively.

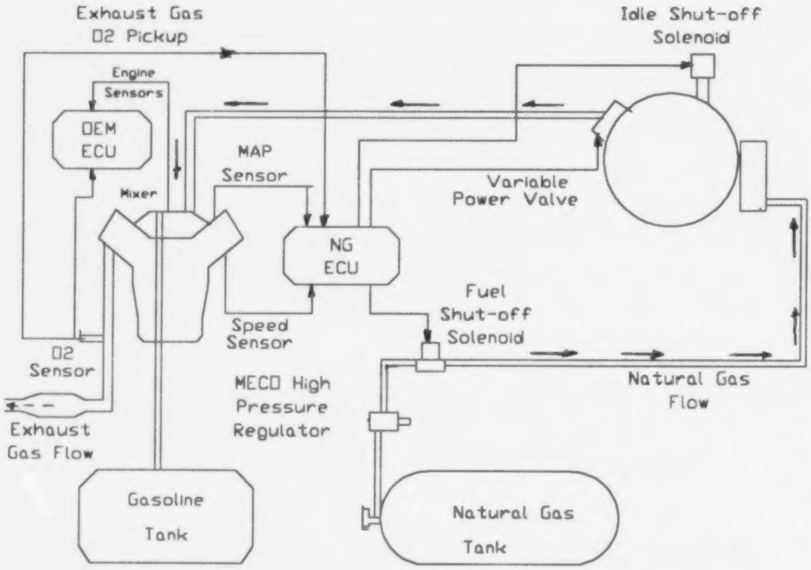
Exhaust Gas
O2 Pickup
Idle Shut-off
Solenoid
Engine
Sensors
OEM
ECU
MAP
Sensor
Mixer
Variable
Power Valve
NG
ECU
Fuel
Shut-off
Solenoid
Speed
Sensor
O2
Sensor
Natural Gas
Flow
MECO High
Pressure
Regulator
Exhaust
Gas Flow
Gasoline
Tank
Natural Gas
Tank

Figure 3.1: Schematic Diagram of a Typical Natural Gas Conversion System

Table 3.1: Comparison of the Conversion Kits Features [26]

	ANGI	GFI	IMPCO	VIALLE
Dual Fuel	yes	yes	yes	yes
Adaptive/Block Learning	no	yes	yes	yes
Feed Forward/Feed Back	no	learn capable	learn capable	program
Closed Loop Operation	no	yes	yes	yes
Spark Control	none	integral	integral	separate MAP based
EGR Control	yes	yes	yes	no
On-Board Diagnostics	hardware and software diagnostics	not available	on-board and software diagonistics	hardware and software diagnostics
Plug-in Wiring Harness	partially complete	field wired	yes	field wired
Digital Speed Density	yes	yes	yes	no
Fuel Switching	automatic	Auto with manual override	auto with manual override	manual
Hot Air Door Operational	no	yes	yes	no
Fuel Distribution	fixed venturi	nozzles	ring	fixed venturi mixer
Air Cleaner Housing Modification	yes (2)	yes (4)	yes (1)	yes (2)
Crankcase Vent Modifications	yes	yes	yes	yes
Automatically Adjusts for Varied Fuel Composition	yes	yes	yes	yes

Table 3.2: Comparison of the Vehicle Conversion Interfaces (in-Kits) [26]

	ANGI	GFI	IMPCO	VIALLE
Throttle Position Sensor (TPS)			X	X
Coolant Temperature Sensor (CTS)			X	
Manifold Absolute Pressure (MAP)	X		X	
Coil Neg	X	X	X	X
Injectors	X	X	X	X
Starter Solenoid		X		X
Knock Sensor		X	X	
O_2 Sensor		X	X	X
Distributor		X	X	
Exhaust Gas Recirculation			X	
Fuel gauge	X	X		

Table 3.3: Comparison of the Vehicle Conversion Interfaces (Add-on) [26]

	ANGI	GFI	IMPCO	VIALLE
Heated O_2		X	X	X
Intake Air Charge		X	X	
Manifold Skin Temperature		X		
Manual Switch		X	X	X
Integral MAP Sensor		X		X
Superfix	X			X
Spark Recurve		integral	integral	
O_2		integral	integral	X

Table 3.4: Qualitative Kit Features - Northwestern Utilities Limited Evaluation (Rating 0-5: 0=poor, 5=excellent) [26]

	ANGI	GFI	IMPCO	VIALLE
Kit Aesthetics	3	2	5	3
Kit Compactness	4	2	3	2
Installation Instructions	3	2	5	3
Wiring Diagrams	4	4	4	2
Ability of Troubleshoot	3	0	2	2
Field Serviceability	3	0	3	3
Ease of Initial Set-up	4	3	5	3
Idle Characteristics	4	5	4	2
Cruise	4	4	4	4
WOT	4	4	4	4
Power	3	4	4	4
Component Placement and Brackets	4	1	5	3
Ease of Component Replacement	3	1	4	3
Warranty	4	1	4	0
Canadian Certification	4	5	4	4
U.S. Certification	5	5	5	4
OEM Quality Components	4	2	5	4
Ease of Installation	3	1	5	3
Equipment Required by Conversion Shop	1	0	5	1
Manufacturer/Supplier Support	4	4	5	1
Feasibility of GM Dealers to do Conversions	4	1	5	3
Technician Training Required to do Conversion	3	2	4	2
TOTAL	**78**	**53**	**94**	**60**

Table 3.5: Material Costs of Base Kits and Accessories [26]

	ANGI	GFI	IMPCO	VIALLE
Base Kit	1,995	2,190	$2,028	$550
Electrical Integration Module				100
Wire and Incidentals		200		
Superfix				
Dual Curve	82			117
Tubing (1.5 lengths)	65	65	65	65
Sherex Receptacle	67	67	67	67
Check Valve	48		48	
O_2 Fix				53
2@ 60 L cylinder	720	720	720	720
2 Cylinder Bracket Kits	210	210	210	210
Frame Support Rail	80	80	80	80
Exhaust Rebuild	130	130	130	130
Base NUL Kit		270		390
S.S. Fittings			30	
HPR 301			48	
Component Mounting Brackets	100	25		7
Shop Supplies		100	50	100
Fuel Gauge			110	110
TOTAL MATERIALS	**$3,497**	**$4,057**	**$3,586**	**$3,065**

Table 3.6: Installation Costs (Labour and materials) [26]

	ANGI	GFI	IMPCO	VIALLE
Electrical and Gas Component	4 hours	20 hours	4 hours	6 hours
Cylinder and Lines	4 hours	4 hours	4 hours	4 hours
Programming and Set-up	3 hours	3 hours	0.5 hours	3 hours
Pre-conversion Vehicle Inspection	2 hours	2 hours	2 hours	2 hours
Component Brackets		2 hours		
TOTAL HOURS	**13 hours**	**31 hours**	**10.5 hours**	**15 hours**
TOTAL LABOUR (@ $50/hr)	**$650**	**$1,550**	**$525**	**$750**
TOTAL MATERIALS	**$3,497**	**$4,057**	**$3,586**	**$3,065**
TOTAL LABOUR AND MATERIALS	**$4,147**	**$5,607**	**$4,111**	**$3,815**

3.2.1 ANGI - Low Emission Vehicle (LEV) System

Truck #1 used a conventional ANGI mixer conversion system consisting of high pressure and low pressure regulators, electrically switched lean cruise/power valve, idle shut-off solenoid, fuel shut-off solenoid, and ANGI mixer. Fuel metering was provided by a venturi upstream of the engine throttle. ANGI is one of the most common systems in use today and is relatively easy to install, tune, and operate. However, the model used in the study was an open loop system and, thus, lacked the feedback capability required to meet the stringent emission standards. The kit was installed with a dual curve ignition system for advancing the spark in order to compensate for the slower burning speed of natural gas. The total installation cost of the kit was $4,147 consisting of $650 for labour and $3,497 for materials. The ANGI kit was rated to be the second-best of all four kits by the Northwestern Utilities, as shown on table 3.4

3.2.2 Stewart and Stevenson/Ortech - Gaseous Fuel Injection (GFI) System

Truck #2, used a pre-production version of the ORTECH/GFI injection system. This is a "high tech" conversion system, incorporating multiple gas injector valves injecting into a gas manifold and, subsequently, through a throttle body spacer ring, under control of a separate engine-control computer. GFI is equivalent to the single-point electronic fuel injection systems found on late model gasoline vehicles. It is a microprocessor-controlled fuel delivery system with rapid response, accurate fuel/air control, and full spark angle control. The kit had the lowest qualitative rating. It was the most expensive of all the kits evaluated with a total installation cost of $5,607 (1,550 for labour and $4,057 for materials).

3.2.3 IMPCO / Air Sensors - Alternative Fuel Electronic (AFE) System

Truck #3, used an IMPCO/Air Sensors kit which incorporated a closed-loop feedback control based on the exhaust gas oxygen sensor and a variable venturi-type mixer. An adaptive-learning programme based on the performance of the engine's closed-loop air/fuel ratio feedback system is incorporated into the IMPCO system software. This adjusts for variations between engines, long term changes in the operating conditions, and the degradation in the engine or the system. The IMPCO kit had the best qualitative rating by the Northwestern Utilities. It had a total installation cost of $4,111 ($525 for labour and $3,586 for materials)

3.2.4 VIALLE - Autogas Management System (AMS)

Truck #4 used the VIALLE conversion kit. The kit had a fixed venturi mixer and an adjustable lean/power valve similar to the ANGI kit for the truck #1. However, it used a stepper motor-controlled power valve instead of a switched-solenoid power valve. The AMS is designed to maintain stoichiometric mixtures, for varying natural gas compositions. It has adaptive/block learn and feed forward/feedback capabilities. The total installation cost of the kit was $3,815 ($3,065 for materials and $750 for labour).

3.3 OPERATION OF NGV CONTROL SYSTEM

One of the most difficult aspects of running an automotive engine on gaseous fuel is the correct metering of the fuel. Natural gas metering systems must compensate for changes in the fuel pressure, fuel composition and quality as well as the normal demands of matching fuel flow to air flow.

The control system of a typical natural gas vehicle (NGV) consists of a network of sensors and other relevant components: some of them from the Original Equipment Manufacturer (OEM), and some from the conversion kit. The main component of the control system is the Electronic Control Unit (ECU). This unit provides the control logic for the fuel carburation (air-fuel ratio), exhaust recirculation, and ignition timing and knock. The ECU receives engine operating parameter inputs from the transducers and sensors, and then sends control signals in response to those parameters as determined by the control software. Figure 3.2 shows a schematic diagram of a typical ECU logic flow [27].

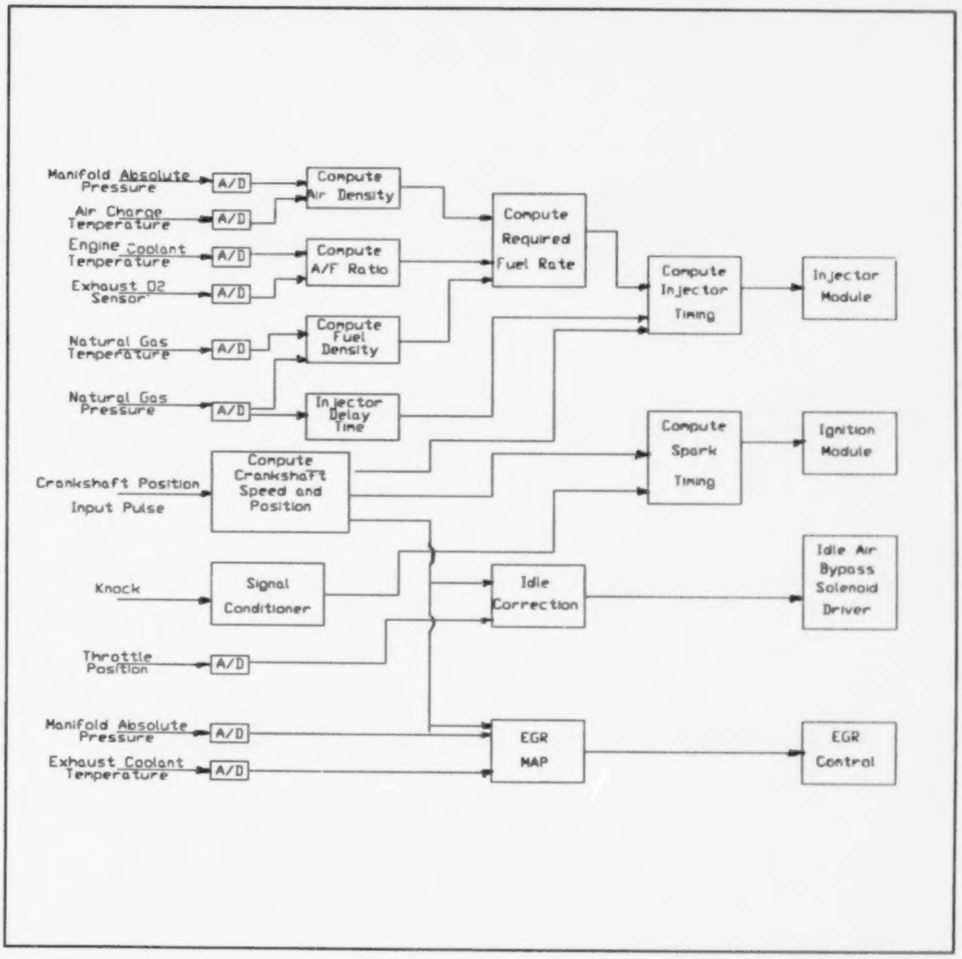
Manifold Absolute Pressure
Air Charge Temperature
Engine Coolant Temperature
Exhaust O2 Sensor
Natural Gas Temperature
Natural Gas Pressure
Crankshaft Position Input Pulse
Knock
Throttle Position
Manifold Absolute Pressure
Exhaust Coolant Temperature
A/D
Compute Air Density
Compute A/F Ratio
Compute Fuel Density
Injector Delay Time
Compute Crankshaft Speed and Position
Signal Conditioner
Compute Required Fuel Rate
Idle Correction
EGR MAP
Compute Injector Timing
Compute Spark Timing
Injector Module
Ignition Module
Idle Air Bypass Solenoid Driver
EGR Control

Figure 3.2: Typical ECU Logic Flow for a GFI Kit Control System

The input parameters include manifold absolute pressure (MAP), air charge temperature (ACT), exhaust coolant temperature (ECT), natural gas temperature and pressure, and the knock count. Also measured are the crankshaft position, the exhaust oxygen concentration, and the throttle position.

The conversion systems for trucks #2, #3, and #4 had closed-loop feedback control systems, while that for truck #1 operated on an open loop mode. For the open-loop mode, the ECU uses input parameters to determine what the air-fuel ratio should be. Once the necessary information is processed, the unit sends appropriate command to the mixture control device. The command does not change until one of the inputs changes. In this mode, the oxygen sensor input is not used and therefore the control unit does not know if the command it sent actually achieved the most appropriate air-fuel ratio for the prevailing operating mode.

The closed-loop mode is an intimate, triangular relationship between the exhaust gas oxygen sensor, the ECU, and the fuel-metering control device to maintain the mixture air-fuel ratio around the stoichiometric value. Signals from the various sensors are sent to the ECU. The unit processes the signal to provide a precisely calculated mixture. This is then compared with the target mixture calibrations and feedback from the oxygen sensor. The results are used to accurately modulate the fuel for stoichiometric closed-loop fuel control. However, this is often very difficult to achieve since the natural gas metering systems must compensate for changes in the fuel and pressure, fuel composition and quality. These are also affected by non-linearity due to mechanical deficiencies in the pressure regulators. Many closed-loop systems incorporate adaptive learning programming. This adjusts for variations between engines, long-term changes in operating conditions and the degradation in the engine or the system.

CHAPTER 4

EQUIPMENT AND PROCEDURE

The testing was carried out using the complete vehicle and drive-train mounted on a drive-shaft chassis dynamometer. A driver in the cab operated the truck, to control the engine speed and dynamometer torque and to provide the most consistent control over a wide range of operating conditions. Each truck was tested over a multi-mode test schedule and at wide-open throttle (WOT) over a range of engine speeds to obtain maximum power and torque curves. For the multi-mode tests, the vehicle transmission was left in "Drive" gear for low power modes, in "2nd" gear for the high power/low speed modes while the "Neutral" gear was used for the idle modes. The 1st and 2nd gears were used for the maximum power/torque tests. Dynamometer torque and speed were measured at the rear wheels to calculate measured power, while the engine torque was inferred from engine speed and measured power (ignoring drive-train losses). For each test configuration, the trucks were tested on both gasoline and natural gas.

The natural gas used for the tests came from the University of Alberta mains supply provided by Northwestern Utilities Limited. It was compressed from the building pressure to approximately 19 MPa by a pair of "Fuelmaker" appliances and then stored in steel cylinders. The cylinders were generally refilled when the pressure had dropped to between 1/2 and 1/3 of full pressure in order to avoid vehicle operating problem and to reduce gas supply variations. In any case, each cylinder always contained enough gas for several tests. Table 4.1 shows the composition of the natural gas used for the test.

Table 4.1: Representative Natural Gas Composition (Analyzed using the MTI P200 Gas Chromatograph)

COMPONENT	CONCENTRATION
Methane	90 %
Ethane	5 %
Nitrogen	5 %
Higher Hydrocarbons	traces

Lower Heating Value: 47.4 MJ/kg [28]
Molecular weight: about 17.3

A single supply of gasoline, Esso, regular unleaded, was used for the test. Fuel was stored in a tank outside the vehicle and was then pumped to the engine. The testing was done in the Engine Laboratory inside the Mechanical Engineering Building. The ambient temperature during the tests varied between 21.0 and 30.9 °C, while the atmospheric pressure had a range of 92.6 to 95.0 kPa.

4.1 TESTING PROCEDURE

4.1.1 The Multi-Mode Test Schedule

For these tests, the trucks were run under steady-state conditions of speed and load in a number of "Modes" comprising the multi-mode Test schedule. Each mode defined an operating condition according to the vehicle speed and drive-shaft power. The multi-mode schedule used in the study is based on a tractive energy analysis of the FTP-78 certification tests and it exercises the vehicle over the same range of speeds and loads as Federal Testing Procedure, FTP-78, while using a set of steady state operating conditions.

These cycles consist of a cold-start Urban driving cycle, FTP-78 (for Federal Test Program -1978), and a warmed-up Highway driving, HWFET, (for Highway Fuel Economy Test). Table 4.2 shows the test modes and the corresponding weighting factors for the Urban and Highway cycles. Table 4.3 shows a summary of the Multi-mode test cycle. These weighting factors are used for obtaining composite results from the individual modal values and they emphasize the operating conditions which are important in normal use.

Table 4.2: Multi-Mode Cycle for the GMC Sierra 2500 3/4 Ton Truck [25]

MODE	Test Speed (km/h)	Test Load (kW)	Urban Power (kW)	Urban Time (s)	Highway Power (kW)	Highway Time (s)
A[1]	0	0	0	71	0	8
B	52	13	13.3	106	13.7	23
C	90	24	24.8	46	23.6	126
D	49	7.5	7.3	185	8.0	10
E	47	4	3.4	122	3.4	4
F	45	23	23	23	21.4	2
G	88	16	15.7	64	16.6	191
H	87	32	33.8	10	31.8	15
I	72	23	24.4	14	23.1	43
J	76	15	13.2	26	15.2	183
K	74	8	7.6	4	7.9	46
L	60	37	36.7	22	33.5	7
M	31	14	14.4	128	19.4	1
N	31	24	24.1	31	21.8	4
O	34	7.5	7.6	81	7.5	0
P	0	0	0	732	0	59

[1] Cold start (mode A) was not used for computing the multi-mode results in this study.

Table 4.3: Multi-Mode Cycle Summary for GMC Sierra 2500 3/4 Ton Truck [25]

	Total Urban Time (s)	Total Urban Distance (km)	Total Urban Energy (kJ)	Total Highway Time (s)	Total Highway Dist. (km)	Total Highway Energy (kJ)
Full Cycle	1878	17.88	12281	765	16.4	11792
Test Modes	1665	12.11	10904	722	14.62	11534
Percent of full Cycle Tested (%)	88.7	67.7	88.8	94.4	89.2	97.8

The multi-mode testing schedule used in the study has a number of advantages over transient testing. Firstly, multi-mode testing with steady operation at each mode avoids many of the equipment and operational complexities inherent in transient testing. This makes the testing simpler, more repeatable, and available at a much lower cost. Also, multi-mode testing provides detailed operating information at several points over the normal driving envelope, rather than just a single result, averaged from several operating conditions. This can be more informative in the development stages since it illuminates the speed/load modes where problems occur and corrections are required. However, the multi-mode schedule is not the official certification standard. For fuel economy and emissions tests, government agencies around the world have been opting for transient testing as the standard. Additionally, multi-mode testing cannot test a vehicle as thoroughly as transient testing since it utilizes only steady-state operating conditions. The cold start, warm-up, and transient over-run conditions, which are critical to hydrocarbons and carbon monoxide emissions of modern vehicles on short drives, are not simulated by steady state multi-mode testing [29]. On the other hand, for heavy commercial vehicles which run for long periods, the transient tests may over-emphasize the cold start.

Multi-Mode Testing Procedure

Several measurements were made during the multi-mode testing. The air consumption rate was monitored using a turbine air meter placed in the air supply ducting, while the fuel mass was continuously measured. A straight line curve fit through the scale output was used to measure the fuel consumption rate. Exhaust gas composition was measured and recorded by various Engine Laboratory equipment, giving readings of carbon monoxide, (CO); oxides of nitrogen, (NOx); carbon dioxide (CO_2), total hydrocarbons (as hexane), (THC); and Oxygen, (O_2). Also monitored were the dynamometer torque and speed, and the dry and wet bulb temperatures. The tailpipe, exhaust (upstream of catalyst) and the emissions sample loop temperatures were also measured. Details of the equipment and calibration are given in table 4.4.

In each mode on the multi-mode test schedule, data for all the measured parameters were taken at one second intervals by a computer-controlled data acquisition system and then averaged over a thirty second period to reduce noise and hence increase the accuracy of the readings. When conditions were stabilized at each mode, the modal readings were then taken and stored in appropriate data files for analysis. Two or more repeat tests (modal readings) were taken at each mode, and provided conditions were acceptable during each repeat, all the repeats were averaged to get a representative value for each mode. However, due to the control limitations of using a full vehicle with the driver and a water-brake dynamometer, not all modes were precisely at the same speed and torque.

Table 4.4: Primary Test Variables Measured By the Dedicated Program

MEASURED QUANTITY	INSTRUMENT MODEL and SERIAL	RANGE	RESOLUTION / REPEATABILITY	CALIBRAT.
Exhaust O_2	Taylor servomex OA.137	0 - 25 %	~0.1%	Room Air (21 %)
Exhaust CO_2	Beckman 864 NDIR	0 - 20 %	~0.05%	% CO_2 5.12 9.77 9.98
Exhaust CO	Beckman 864 NDIR	0 - 1 % 0 - 5 %	~0.01%	% CO 0.10 0.95
Exhaust THC (as Hexane)	Beckman GC 72.5 FID	0-1000 ppm	~1 ppm	ppm CH_4 98 990 ppm C_6H_{14} 517
Exhaust NOx	Beckman 955 Chemiluminescent	0 - 250 ppm 0 - 500 ppm 0 -1000 ppm	~1 ppm	ppm NO 242 515
Dynamometer Speed	F/V on Dyno Speed	0-200 km/h	0.1 km/h	Electronic Counter
Dynamometer Torque	Validyne on Load cell	0-1000 N.m	0.2 N.m	Stand. Weight
Fuel Consumption	Pacific Scale	0 - 60 kg	5 g scale resolution (~1 g with averaging)	Stand. weight
Air Consumption	F/V on Turbine Meter	0-200 L/s	0.15 L/s	Standard Orifice

Gas Chromatography

A MIT P200 gas chromatograph attached to a 80386-based PC-compatible computer was used to measure the exhaust gas composition on a sample-by-sample basis. The primary purpose was to obtain the exhaust gas methane concentration. Table 4.5 shows the quantities measured by gas chromatography.

Table 4.5: Exhaust Emissions Measured with the Gas Chromatograph

MEASURED QUANTITY	UNITS	CALIBRATION
CH_4 Concentration	ppm	98 ppm CH_4 990 ppm CH_4
CO_2 Concentration	%	5.12 % CO_2 9.77 % CO_2 9.98 % CO_2
CO Concentration	%	0.95 % CO 0.10 % CO
NO Concentration	ppm	242 ppm NO 515 ppm NO

4.1.2 Wide-Open Throttle Tests

In the high power mode testing, the trucks were run at maximum throttle for brief periods to measure maximum torque and power curves. The vehicles were initially warmed-up to a coolant temperature of between 94 °C and 95 °C. With the transmission in first gear, the throttle was rapidly opened and the dynamometer load adjusted to stabilize the dynamometer speed. As in the multi-mode testing, all parameters were measured at one second intervals by the computer and then averaged over a fifteen second period to provide each measurement. The 15 second period was used to reduce noise and increase accuracy, while avoiding excessive engine strain and overheating. After each test, the engine was idled until the coolant temperature had dropped to about 95 °C. Tests were repeated with a different dynamometer load and speed at intervals determined by the coolant temperature. Vehicle cooling was provided by a constant speed fan placed in front of the truck. Full throttle data for each vehicle configuration were recorded over a speed range to develop power and torque curves.

4.1.3 Equipment and Software

4.1.3.1 Exhaust Gas Analysis System

Figures 4.1 shows a schematic diagram of the exhaust gas sampling system. The exhaust gas was sampled alternately from two points: one point was upstream of the catalyst and the other point was at the tailpipe (downstream of the catalyst). The sampling of the exhaust from the two points was done in order to evaluate the performance of the catalytic converter. The extracted exhaust gas was first passed through a cooler bath to remove water vapour, and then through a filter to remove particulate impurities. The exhaust was then channelled to the gas analyzers via two sampling loops at above-atmospheric pressure. A pressure regulator installed in the sampling line helped to maintain exhaust gas pressure at a constant value of 4.75 psi (33 kPa) in the measuring equipment. Figure 4.2 shows a schematic diagram of loop 1. The loop contains a BECKMAN 955 Chemi-Luminescent oxides of nitrogen (NOx) analyzer;

and a BECKMAN GC-72 Flame Ionization Detector (F.I.D.) for measuring the total hydrocarbons concentration (as hexane). Loop 2 contains a Taylor Servomex oxygen (O_2) analyzer, a BECKMAN 864 Non-dispersive Infrared (NDIR) carbon dioxide (CO_2) analyzer, a BECKMAN 864 NDIR carbon monoxide (CO) analyzer, and a MTI P200 Gas Chromatography (G. C.). The G. C. was primarily used for obtaining the methane concentration. This is illustrated in figure 4.3.

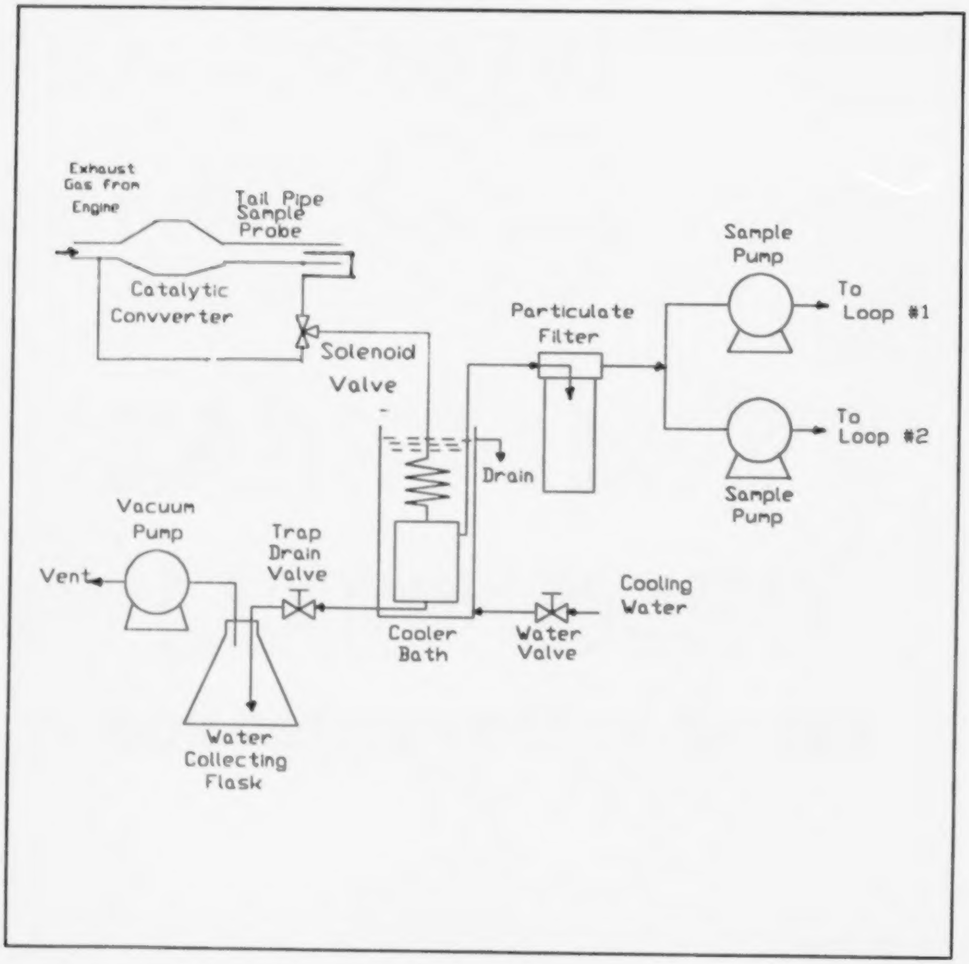
Exhaust Gas from Engine
Tail Pipe Sample Probe
Catalytic Convverter
Solenoid Valve
Particulate Filter
Sample Pump
To Loop #1
To Loop #2
Sample Pump
Drain
Vacuum Pump
Vent
Trap Drain Valve
Cooling Water
Cooler Bath
Water Valve
Water Collecting Flask

Figure 4.1: Exhaust Sample Handling System

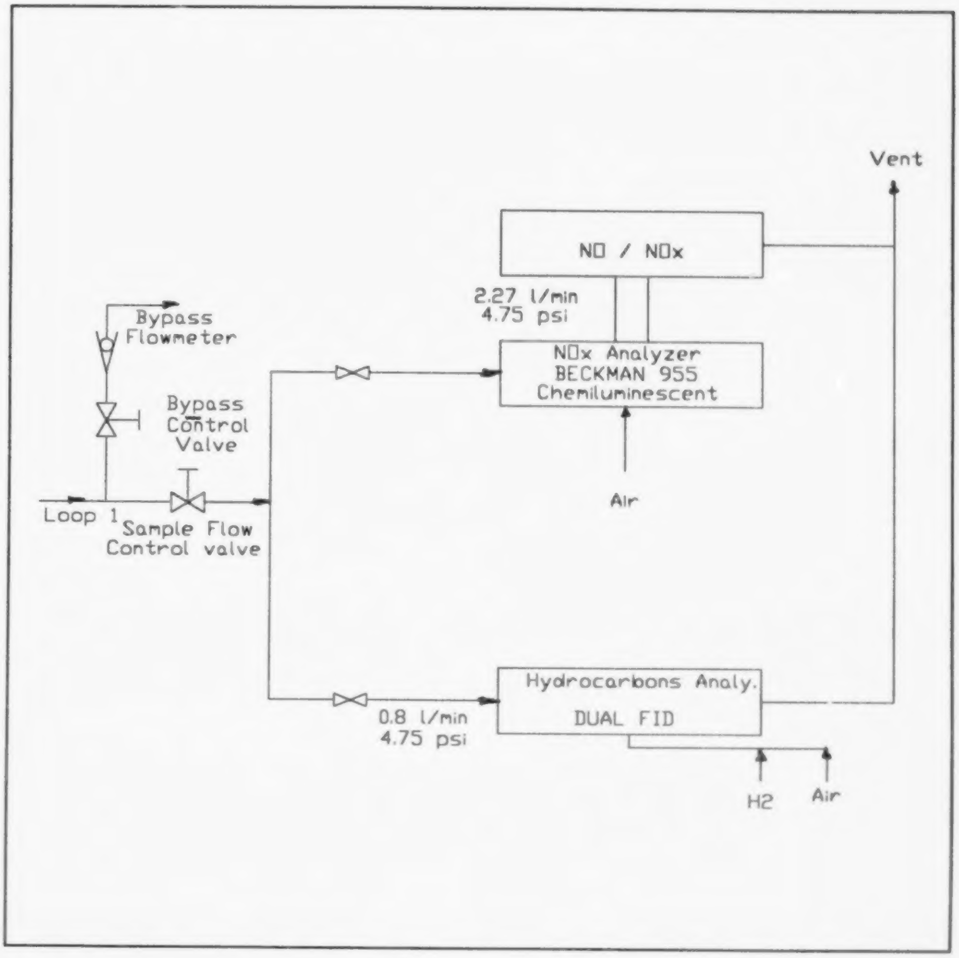
Vent
NO / NOx
2.27 l/min
4.75 psi
Bypass
Flowmeter
NOx Analyzer
BECKMAN 955
Chemiluminescent
Bypass
Control
Valve
Air
Loop 1
Sample Flow
Control valve
Hydrocarbons Analy.
DUAL FID
0.8 l/min
4.75 psi
H2
Air

Figure 4.2: Loop #1 of Exhaust Gas Analysis System

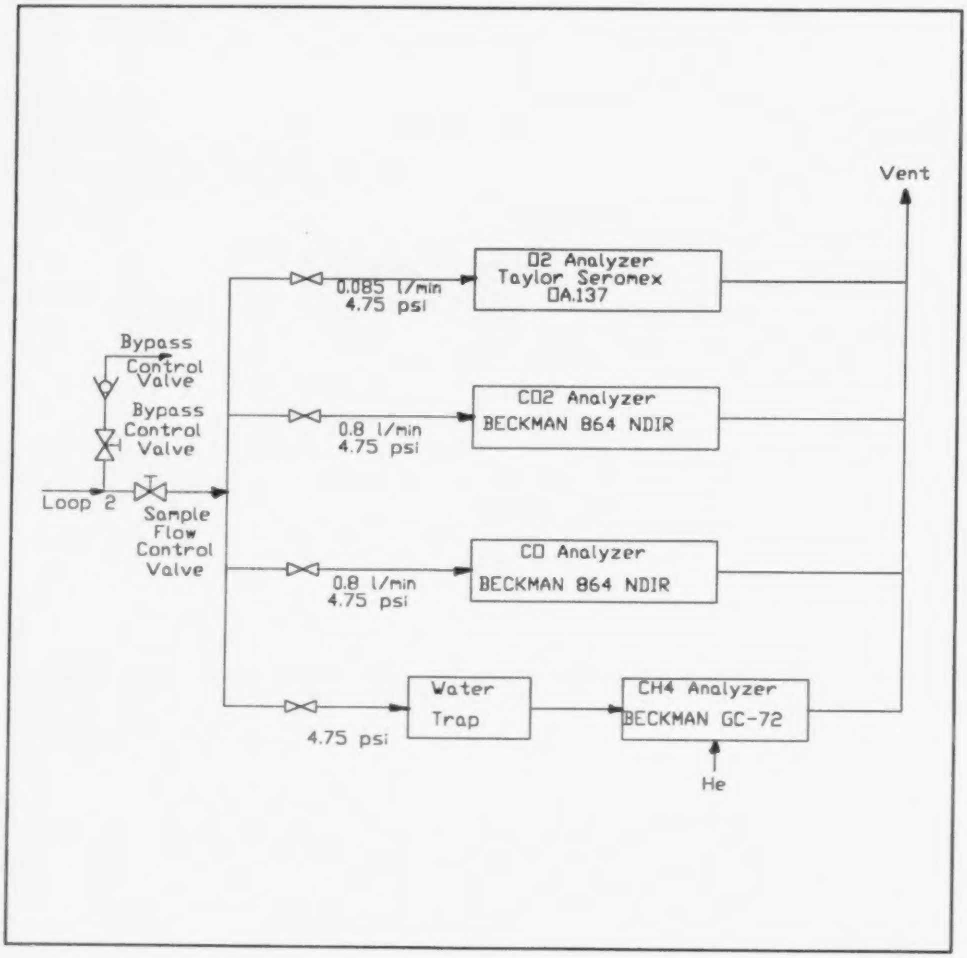
Vent
O2 Analyzer
Taylor Seromex
OA.137
0.085 l/min
4.75 psi
Bypass
Control
Valve
Bypass
Control
Valve
CO2 Analyzer
BECKMAN 864 NDIR
0.8 l/min
4.75 psi
Loop 2
Sample
Flow
Control
Valve
CO Analyzer
BECKMAN 864 NDIR
0.8 l/min
4.75 psi
Water
Trap
CH4 Analyzer
BECKMAN GC-72
4.75 psi
He

Figure 4.3: Loop #2 of the Exhaust Gas Analysis System

Gas Analyzers Calibration

The front panel readout and the output voltages of the gas analyzers were calibrated using standard calibration gases. To calibrate each analyzer, its zero reading was checked by supplying it with a zero gas, that is, a gas that did not contain the gas that the analyzer detects. The zero on the meter was often adjusted in order to obtain a zero output voltage. Then the span gases were supplied, with the meter readings and output voltages noted. Various calibration equations were then obtained using least squares curve fits. The CO, CO_2, and O_2 calibration equations were linear while that for the FID (THC) was a second-order polynomial. Table 4.6 shows the calibration gases used for the testing.

Table 4.6: Calibration Gases Used in the Study

GAS	CO (%)	CO_2 (%)	O_2 (%)	NO (ppm)	CH_4 (ppm)	C_6H_{14} (ppm)
1			21			
2			21		98	
3	0.95					
4		5.12				
5		9.77				
6	0.10	9.98			990	
7						517
8				242		
9				515		

4.1.3.2 Data Acquisition Programs

Dedicated Programs

For all the tests, the primary test variables were measured, displayed and recorded continuously by the dedicated programs running on an AT-compatible computer using a Metrabyte DAS-16 data acquisition card and multiplexer cards. The programs, NULTRUCK and NULSTRIP were written in QUICKBASIC.

A. NULTRUCK

This was the program for data acquisition, calibration and strip chart display of multiple channels of data. It was used for measuring truck performance and emissions on a multi-mode cycle or for peak power and torque readings. It used VGA graphics (screen 12, 60 lines) and required DAS-16G1 and EXP-16 boards. The program used an input setup file containing information on how many channels to read, what channels to read, their names and units, how often to read them, and what calibration equations to use. This information was then incorporated into the program and acted upon to display a continuous strip chart with the option of a continuous record. The program also had a capability of changing the sample averaging period, for the displayed data, on key commands.

The measurements made by the program included the dynamometer torque and speed, exhaust temperature, exhaust sample temperature and the water bath temperature. Also measured were the air temperature, fuel consumption, air consumption, exhaust gas composition, and relative humidity. These were often recorded as binary data on a file.

B. NULSTRIP

This program was used to read data from the output files produced by NULTRUCK for further review so that new modes could be saved, or so that the data could be manipulated for further deductions. It basically performed the same functions as the NULTRUCK but used the recorded second-by-second data files as input rather than reading live data.

C. McKARNEY SYSTEM

This is an engine-control-computer (ECC) monitoring system that operated in an AT-compatible computer and communicated directly with the GM ECC. It provided additional monitoring of the running state of the vehicle and provided information on how the conversion system modifications were interacting with the original engine control.

This system displayed and recorded engine sensor outputs as processed by the engine control computer and alerted the testers to any engine malfunction by displaying error codes. The engine variables monitored included the coolant temperature sensor (CTS), knock count, manifold absolute pressure (MAP), exhaust oxygen (O_2), engine speed, vehicle speed, air-fuel mixture control (closed or open loop), and air-fuel ratio (lean or rich). Snapshots of data stream were recorded with most modes.

4.2 DATA REDUCTION

After the tests were conducted, the recorded data were often reviewed using the NULSTRIP program in order to ensure that the tests were carried out at ideal conditions. The program was also used to save new modes, or to facilitate other manipulations necessary for further data deduction.

4.2.1 Multi-Mode Data Reduction

For the multi-mode tests, a QUICKBASIC program, MODANALY was written for data reduction. The program essentially does the following :

1. Locates and reads recorded data files for each mode of a particular test.
2. Averages all the recorded data for the repeats for a particular mode to get representative values for the mode.
3. Calculates the composite values for the emissions and fuel flow rates in g/km and kg/100 km, respectively. It uses the mode weighting factors from table 4.2 which is based on a 55 %/45 % balance between the Urban and Highway cycle values.
4. Calculates the catalytic converter efficiencies for each exhaust gas components.

4.2.1.1 Results for each Test Mode

The program calculates the total exhaust composition from the dry composition and then using the total air and fuel flow, obtains the emissions on a mass basis.

1. Calculation of Molar Fractions on Dry Basis

From the measured exhaust gas concentrations, the program calculates the molar fractions of the measured components in the dry exhaust gas:

$$yCO_{dry}=CO_{per}/100 \tag{4.1}$$

$$yO_{2_{dry}}=O_{2_{per}}/100 \tag{4.2}$$

$$yCO_{2_{dry}}=CO_{2_{per}}/100 \tag{4.3}$$

$$yNO_{dry}=NOx_{ppm}/1000000 \tag{4.4}$$

$$yCH_{4_{dry}}=CH_{4_{ppm}}/1000000 \tag{4.5}$$

Where CO_{per}, O_{2per}, CO_{2per}, NOx_{ppm}, CH_{4ppm}, are the concentrations of carbon monoxide, oxygen, carbon dioxide, oxides of nitrogen, and methane, in the dry exhaust gas, respectively. yCO_{dry}, yO_{2dry}, yCO_{2dry}, yNO_{dry}, yCH_{4dry}, are the molar fractions of carbon monoxide, oxygen, carbon dioxide, oxides of nitrogen, and methane in the dry exhaust gas, respectively.

The total hydrocarbons FID reading is approximated as hexane and the program subtracts off the methane composition to obtain the reactive hydrocarbons (RHC) value:

$$yTHC_{dry}=THC_{ppm}/1000000 \tag{4.6}$$

$$yRHC_{dry}=yTHC-yCH_4/6 \tag{4.7}$$

THC_{ppm}, and RHC_{ppm} are the concentrations of total hydrocarbons, and reactive hydrocarbons in the dry exhaust gas, respectively. $yTHC_{dry}$ and $yRHC_{dry}$ are the molar fractions of total hydrocarbons, and reactive hydrocarbons in the dry exhaust gas, respectively.

The saturated vapour pressure at the dry bulb temperature, P_{sat}, is calculated:

$$P_{sat}=\exp(c_1/t_{dry}+c_2+c_3\times t_{dry}+c_4\times t_{dry}^2+c_5\times t_{dry}^3+c_7\times\log(t_{dry}))/1000 \tag{4.8}$$

Where c_1, c_2, c_3, c_4, c_5, c_6, and c_7 are constants, and t_{dry} is the dry bulb temperature.

The mole fraction of the water vapour, yH_2O_{dry} is then approximated:

$$yH_2O_{dry}=P_{sat}/P_{barom} \tag{4.9}$$

Where P_{barom} is the barometric pressure in kPa.

The remainder of the emission flow rate is taken to be nitrogen, yN_{2dry}:

$$yN_{2_{dry}}=1-(yCO_{dry}+yCO_{2_{dry}}+yO_2dry+yTHC_{dry}+yH_2O_{dry}+yNO_{dry}) \tag{4.10}$$

2 Determination of Unknown Emission Component Molar Fractions

The combustion equation for a hydrocarbon in air is given by:

$$C_xH_y+fO_2+3.76fN_2\rightarrow aCO_2+bO_2+dCO+eN_2+gH_2O+jC_6H_{14}+kNO \qquad (4.11)$$

Where a, b, c, d, j and k are the known coefficients, while f, e, g, x and y are the unknown coefficients.

The principle of conservation of mass, is used to solve for the unknown coefficients

Carbon balance :

$$x=yCO_{dry}+yCO_{2_{dry}}+6\times yTHC_{dry} \qquad (4.12)$$

Nitrogen balance :

$$f=(yN_{2_{dry}}+.5yNO_{dry})/3.76 \qquad (4.13)$$

Oxygen balance :

$$g=2\times(f-yCO_{2_{dry}}-yO_{2_{dry}}-0.5\times yCO_{dry}-0.5\times yNO_{dry}) \qquad (4.14)$$

Obtain a more accurate value of the molar fraction of water vapour:

$$yH_2O_{dry}=g \qquad (4.15)$$

Hydrogen balance :

$$y=2\times g+14\times yTHC_{dry} \qquad (4.16)$$

The Hydrogen to Carbon ratio is then:

$$H/C=\frac{y}{x} \qquad (4.17)$$

and air-fuel ratio inferred from emissions, AF_{em}:

$$AF_{em}=4.76\times f\times M_{air}/(12x+y) \qquad (4.18)$$

and air-fuel ratio measured directly from mass, AF_{mas}:

$$\mathbf{AF_{mas}}=\textbf{ mass flow rate of air / mass flow rate of fuel} \qquad (4.19)$$

3. Calculation of Molar Fractions on Wet Basis

The mole fraction of water vapour is added to the dry exhaust and the composition of the wet exhaust gas prior to water trap is recalculated to include water vapour:

$$Exh_{wet}=yH_2O_{dry}+1 \qquad (4.20)$$

$$yCO_{2_{wet}}=yCO_{2_{dry}}/Exh_{wet} \qquad (4.21)$$

$$yCO_{wet}=yCO_{dry}/Exh_{wet} \qquad (4.22)$$

$$yCH_{4_{wet}}=yCH_{4_{dry}}/Exh_{wet} \qquad (4.23)$$

$$yTHC_{wet}=yTHC_{dry}/Exh_{wet} \tag{4.24}$$

$$yO_{2_{wet}}=yO_{2_{dry}}/Exh_{wet} \tag{4.25}$$

$$yNO_{wet}=yNO_{dry}/Exh_{wet} \tag{4.26}$$

$$yN_{2_{wet}}=yN_{2_{dry}}/Exh_{wet} \tag{4.27}$$

$$yH_2O_{wet}=yH_2O_{dry}/Exh_{wet} \tag{4.28}$$

$$yRHC_{wet}=yRHC_{dry}/Exh_{wet} \tag{4.29}$$

Where yCO_{2wet}, yCO_{wet}, yCH_{4wet}, $yTHC_{wet}$, yO_{2wet}, yNO_{wet}, yN_{2wet}, yH_2O_{wet}, and $yRHC_{wet}$ are the molar concentrations of carbon dioxide, carbon monoxide, methane, total hydrocarbons, oxygen, oxides of nitrogen, nitrogen, water vapour, and reactive hydrocarbons in the wet exhaust gas, respectively.

The molar mass of the exhaust gas (wet basis), M_{exh}, is calculated by adding the product of the molar fractions on wet basis and the molar weights of each of the exhaust components:

$$M_{exh}=44.01\times yCO_{2_{wet}}+28.01\times yCO_{wet}+32\times yO_{2_{wet}}+18.01\times yH_2O_{wet}+28.01\times yN_{2_{wet}}$$

$$+46\times yNO_{wet}+86\times yTHC_{wet} \tag{4.30}$$

The total exhaust mass flow rate Em_{flow} (grams per second) is calculated as flows:

$$Em_{flow} = \text{air flow} + \text{fuel flow} \tag{4.31}$$

4. Calculation of Mass Flow Rate of Components in Grams per Second

The mass flow rate of the individual components, in grams per second, are then calculated from the total mass flow and the molar fractions (wet basis):

$$mCO_{2_{gps}} = yCO_{2_{wet}} \times 44.01/M_{exh} \times Em_{flow} \tag{4.32}$$

$$mCO_{gps} = yCO_{wet} \times 28.01/M_{exh} \times Em_{flow} \tag{4.33}$$

$$mO_{2_{gps}} = yO_{2_{wet}} \times 32/M_{exh} \times Em_{flow} \tag{4.34}$$

$$mH_2O_{gps} = yH_2O_{wet} \times 18.01/M_{exh} \times Em_{flow} \tag{4.35}$$

$$mN_{2_{gps}} = yN_{2_{wet}} \times 28.01/M_{exh} \times Em_{flow} \tag{4.36}$$

$$mNOx_{gps} = yNO_{wet} \times \left(\frac{46}{30}\right)/M_{exh} \times Em_{flow} \tag{4.37}$$

$$mCH_{4_{gps}} = yCH_{4_{wet}} \times 16/M_{exh} \times Em_{flow} \tag{4.38}$$

$$mTHC_{gps} = yTHC_{wet} \times 86/M_{exh} \times Em_{flow} \tag{4.39}$$

$$mRHC_{gps} = yRHC_{wet} \times 86/M_{exh} \times Em_{flow} \tag{4.40}$$

Where mCO_{2gps}, mCO_{gps}, mO_{2gps}, mH_2O_{gps}, mN_{2gps}, $yNOx_{gps}$, mCH_{4gps}, $mTHC_{gps}$, and $mRHC_{gps}$, are the mass flow rates (in grams per second) of carbon dioxide, carbon monoxide, oxygen, water vapour, nitrogen, oxides of nitrogen, methane, total hydrocarbons, and reactive hydrocarbons, in the dry exhaust gas, respectively.

5. Calculation of the Brake Specific Exhaust Flow Rates

The brake specific exhaust flow rates in gram per kilowatt hour (g/kW.h) are calculated from the mass flow rates in grams per second (g/s) by multiplying by 3600 seconds and then dividing by the brake power, $\mathrm{Power}_{\mathrm{brake}}$, in kW:

$$bsCO_{2_{gkh}} = mCO_{2_{gps}} \times 3600/Power_{brake} \tag{4.41}$$

$$bsCO_{gkh} = mCO_{gps} \times 3600/Power_{brake} \tag{4.42}$$

$$bsO_{2_{gkh}} = mO_{2_{gps}} \times 3600/Power_{brake} \tag{4.43}$$

$$bsH_2O_{gkh} = mH_2O_{gps} \times 3600/Power_{brake} \tag{4.44}$$

$$bsN_{2_{gkh}} = mN_{2_{gps}} \times 3600/Power_{brake} \tag{4.45}$$

$$bsNOx_{gkh} = mNOx_{gps} \times 3600/Power_{brake} \tag{4.46}$$

$$bsCH_{4_{gkh}} = mCH_{4_{gps}} \times 3600/Power_{brake} \tag{4.47}$$

$$bsTHC_{gkh} = mTHC_{gps} \times 3600/Power_{brake} \tag{4.48}$$

$$bsRHC_{gkh} = mRHC_{gps} \times 3600/Power_{brake} \tag{4.49}$$

Where $bsCO_{2gkh}$, $bsCO_{gkh}$, bsO_{2gkh}, bsH_2O_{gkh}, bsN_{2gkh}, $bsNOx_{gkh}$, $bsCH_{4gkh}$, $bsTHC_{gkh}$, and $bsRHC_{gkh}$ are the brake specific flow rates (in grams per kilowatt-hour) of carbon dioxide, carbon monoxide, oxygen, water vapour, nitrogen, oxides of nitrogen, methane, total hydrocarbons, and reactive hydrocarbons, respectively.

The vehicle speed is calculated from the dynamometer speed:

$$Veh.Speed = Dyno.Speed \times tireradius \times 2 \times \Pi \times 60/1000/axleratio \tag{4.50}$$

Where the dynamometer speed (Dyno.speed) and tire radius (tireradius) are in revolutions per second (rpm) and meters, respectively.

Then the brake specific fuel consumption is calculated in kg/kW.h:

$$\textbf{Brake Specific fuel consumption} = \textbf{fuel flow rate} * 3600 / \textbf{Power}_{\textbf{brake}} \tag{4.51}$$

6. Catalytic Converter Performance

On a mode by mode basis, the program calculates the catalytic converter conversion efficiencies for the various exhaust emission components (CO, NOx, RHC, THC, and CH_4).

$$Conversion_{Efficiency} = (UP_{Emission} - DOWN_{Emission}) / UP_{Emission} \tag{4.52}$$

Where $UP_{Emission}$ and $DOWN_{Emission}$ are the mass flow rates of the exhaust component, upstream and downstream of the catalyst, respectively.

For example

$$CO\% = (CO_{upstream} - CO_{downstream})/CO_{upstream} \tag{4.53}$$

The prog[illegible] then calculates a simple average of all the repeats for each mode, for each of the calculated results (exhaust emission components and fuel consumption), in order to obtain a representative value for each operating mode. The program also calculates the relative deviations of the data from the various repeats of a particular mode.

4.2.1.2 Composite Results

A single composite value for each of the exhaust components is then calculated in g/km for the exhaust emission components or kg/100 km for fuel consumption. These composite results are obtained by taking a weighted average of the 15 modes comprising the multi-mode test schedule (cold starts were not included). The mode weighting factors in table 4.2. are used for these compilations. The factors emphasize the operating conditions which are important in normal use. The following are the steps used in the program for computing the composite results:

1. A power correction is used to make adjustments for modes which may not have been run at the exact power. This is done by multiplying the various mode emission rates, fuel consumption and air consumption in grams per second by the power correction factor. Where

Power Correct. Factor = (Actual Mode Power)/ (Ideal Mode Power) (5.54)

These are done for both the Urban and Highway cycles.

2. The corrected mass flow rates are multiplied by the ideal cycle times, for both the Urban and Highway Cycles, to obtain the total consumptions and emissions (in grams) for each individual mode.

3. The fuel consumption and emission rates for each tested mode are added to obtain the total mass values for the Urban and Highway cycles. These may or may not include cold starts. For these particular tests, cold starts were not included.

4. The total values for the Urban and Highway cycles are divided by the total distance travelled for the cycles (17.88 km and 16.4 km, respectively from Table 4.2) to give a weighted value for each cycle, in g/km for the emissions, and kg/100 km for the fuel consumption.

5. The composite fuel and emission results are computed based on a 55 % Urban and 45 % Highway basis.

4.2.2 Wide-Open Throttle Tests Data Reduction

For the High-Power mode tests, a dedicated program was written for data reduction. This program essentially converts all maximum power and torque results to standard atmospheric conditions according to SAE J1349 [30]. It then fits a polynomial to each of the torque/speed and power/speed data sets, respectively. It also interpolates for maximum torque, torque at 2000 rpm, maximum power, and power at 4000 rpm.

The SAE J1349 correction factors applied to the observed power and torque account for the difference between the reference air conditions (density) and those at which the test data were taken. This helps to provide a common basis of comparison for various operating conditions since the performance of SI engines is affected by the density of the inlet combustion air.

$$power_{corrected} = air_{factor} \times power_{observed} \tag{4.55}$$

$$air_{factor} = 1.18[(99/P_{total})(t_{dry}/298)^{.5}] - 0.18 \tag{4.56}$$

$$P_{total} = \frac{P_{barom}}{760} \times 101.325 - P_v \tag{4.57}$$

Where,

$\mathrm{power}_{\mathrm{observed}}$ = Observed brake power

$\mathrm{power}_{\mathrm{corrected}}$ = Corrected brake power

$\mathrm{air}_{\mathrm{factor}}$ = Air correction factor

$\mathrm{P}_{\mathrm{total}}$ = Inlet air supply total pressure, kPa

$\mathrm{t}_{\mathrm{dry}}$ = Inlet air supply temperature (dry bulb), K

$\mathrm{t}_{\mathrm{wet}}$ = Inlet air supply temperature (wet bulb), K

$\mathrm{P}_{\mathrm{barom}}$ = Barometric pressure, mm.Hg

P_{v} = Atmospheric vapour pressure, kPa

4.3 REPEATABILITY AND ACCURACY OF MEASUREMENTS AND CALCULATED VALUES

No measurement is worthwhile unless it is repeatable within acceptable accuracy. It is necessary to determine the uncertainty of individual measurements, and of calculated results and then to ascertain if the differences between calculated results are significant considering the measurement uncertainty.

Most of the test variables were monitored, displayed and recorded as 30 second time averages by a computer to reduce the variability in the measurement. Generally, two to four repeat measurements (30 s averages) were taken at each test mode. The variability between these measurements then provides an estimate of experimental uncertainty associated with each measurement and with the calculated composite, multi-mode test results.

Table 4.7 shows the typical relative standard deviation between repeated emission and fuel consumption measurements for both gasoline and natural gas at single test points during the testing. The variabilities of NOx, CO, RHC and CH_4 were high (7 to 18 %) because of the low average emission values which helped to increase the relative deviation appreciably. The fuel consumption had low variability, (3 or 4%), due to the precise fuel mass and time measurements, while for CO_2, a major component of the exhaust mixture, measurement was generally very accurate (1%).

Table 4.7: Relative Standard Deviation in Repeat Measurements at a Single Test Point. (± 1 standard deviation, averages for all modes)

	GASOLINE	**NATURAL GAS**
CO	11 %	13 %
CO_2	1%	1 %
NOx	17 %	8 %
RHC	14 %	18 %
CH_4		7 %
Fuel Consumption	3 %	4 %
A/F Equivalence Ratio	4 %	5 %

Multiple measurements were made in order to reduce the variability of individual measurements. By averaging these repeat measurements, the uncertainty of the averages are reduced by $1/\sqrt{n}$ times the individual uncertainty. Since at least two repeat measurements were made at each test mode, the single measurement variability is thus multiplied by $1/\sqrt{2} = 0.707$ to obtain the variability of each mode data. The variability of multi-mode test result is obtained by multiplying the single measurement value by $1/\sqrt{(2*15)} = 0.183$ since the composite values were obtained by averaging data from 15 modes. Tables 4.8a and 4.8b give the uncertainty in single point, mode and multi-mode tests results for gasoline and natural gas, respectively.

Table 4.8a: Uncertainty in Mode and Multi-mode Tests Results For Gasoline (± 1 standard deviation on repeatability analysis of single measurements in multi-mode tests)

	SINGLE TEST POINT	1 MODE (At least 2 Test Points)	MULTI-MODE (15 Modes)
CO	11 %	8 %	2 %
CO_2	1 %	0.7 %	0.2 %
NOx	17 %	12 %	3 %
RHC	14 %	10 %	2.5 %
Fuel Consumption	3 %	2 %	0.5 %
A/F Equivalence Ratio	4 %	3 %	1 %

Table 4.8b: Uncertainty in Mode and Multi-mode Tests Results For Natural Gas (± 1 standard deviation based on repeatability analysis of single measurements in multi-mode tests)

	SINGLE TEST POINT	1 MODE (At least 2 Test Points)	MULTI-MODE (15 Modes)
CO	13 %	9 %	2 %
CO_2	1 %	1 %	0.2 %
NOx	8 %	6 %	1.5 %
RHC	18 %	13 %	3 %
CH_4	7 %	5 %	1 %
Fuel Consumption	4 %	3 %	1 %
A/F Equivalence Ratio	5 %	4 %	1 %

The measurement uncertainty in multi-mode composite results is very low (2 % to 3 %) and is rather an optimistic estimate of how accurately the tests can be performed. Certain systematic factors such as changes in the atmospheric conditions, vehicle operation (driving), dynamometer operation and shifts in emissions analyzers calibration would tend to produce larger shifts in results. Hence the true uncertainty of measurement for the multi-mode tests results is slightly higher than the values obtained in the study.

CHAPTER 5

RESULTS AND DISCUSSION

Four light-duty trucks, each fitted with a different natural gas conversion kit, were tested on gasoline and natural gas fuels. Each truck was tested on a multi-mode schedule to obtain the modal emission and fuel consumption rates. These modal values were then combined into single composite values using weighting factors based on the FTP-78 Urban and Highway Test Schedules. The trucks were also run at wide-open-throttle (WOT) to measure the brake power/speed and torque/speed curves. The graphs of the brake specific emissions (upstream and downstream of the catalytic converter) and fuel consumption rates against brake power for the multi-mode tests are presented in the chapter. Also presented are the brake power and brake torque curves for the wide-open throttle testing. Appendix A gives the multi-mode composite emissions and fuel consumption results for the trucks while running on gasoline and natural gas. Also given are the peak power and peak torque results at maximum throttle. Appendix B gives the raw experimental results.

5.1 MULTI-MODE TESTS RESULTS

5.1.1 Equivalence Ratio

Precise control of the equivalence ratio is necessary to minimize emissions from spark-ignition engines while maintaining good performance and fuel economy. Also, the performance of 3-way catalytic converters, which help in the reduction of exhaust emissions depends on the control of the air-fuel ratio in a narrow window about the stoichiometric value. The conversion efficiencies of the hydrocarbons (HC) and carbon monoxide (CO) are lost very rapidly as the mixture goes rich, while the oxides of nitrogen (NOx) conversion efficiency declines almost precipitously as the mixture moves lean. Therefore, the engines are typically operated with stoichiometric air-fuel ratios using closed-loop electronic feedback control from an exhaust gas oxygen sensor (O_2 sensor).

There was no clear relationship between the air-fuel equivalence ratio and power, at normal power levels, for all the trucks while being fuelled by gasoline or natural gas. Figures 5.1a, 5.1b, 5.1c and 5.1d present the plots of equivalence ratio (on mass basis) as a function of brake power for the multi-mode tests. The equivalence ratios based on the exhaust emissions were also computed but were found to be less reliable than those obtained directly from the air and fuel mass flow rates. This is mainly due to the less precise measurements obtained with the gas analyzers compared with those obtained with the mass flow rate instruments. The plots also show that the equivalence ratio for the idle modes on natural gas were rather low because of the error in measurement of small gas flow rates.

On gasoline, the average equivalence ratio varied between 0.92 for truck #1 (ANGI-open-loop) and 1.05 for #4 (VIALLE-AMS) with a mean value of 0.97 and a relative deviation of 4.9 %. On natural gas, for the trucks with closed-loop conversion systems, the range was between 0.91 for #3 (IMPCO-Air Sensors,Englehard Catalyst) and 0.98 for #4 (VIALLE-AMS) with a mean value of 0.94 and a relative deviation of 3.3 %. The variability between the air-fuel equivalence ratio of the trucks during natural gas operation was low. The truck with the open-loop conversion (ANGI) operated leaner on natural gas with a mean equivalence ratio of 0.83. The ratio was found to increase with power for this particular truck.

The leaner operation of the trucks on natural gas is also evident in the amount of excess oxygen in the exhaust. Figures 5.2a, 5.2b, 5.2c and 5.2d show the excess O_2 as a function of brake power. A comparison of the composite O_2 results is given in figure 5.3. For the gasoline operation, the composite O_2 emission values ranged between 12.3 and 14.4 g/km with a mean value of 13.3 g/km. On natural gas, the mean value O_2 was 39.6 g/km with a range of 19.2 to 54.8 g/km.

The fact that the trucks ran leaner on natural gas is surprising in these feedback-controlled vehicles. This could be due to a bias in the readings provided by the oxygen sensor during the gaseous fuel operation. The sensor could be affected by higher values of hydrogen than present in normal gasoline exhaust because of the higher hydrogen-to-carbon ratio of natural gas. Higher exhaust hydrogen values normally imply richer mixture operation, hence the engine is made to run leaner.

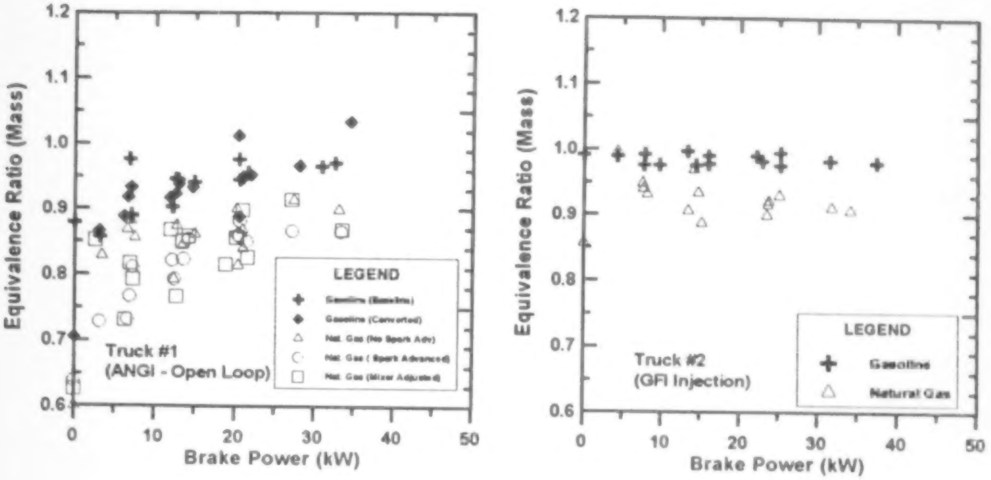

Figure 5.1a: Truck #1 (ANGI Open-Loop)

Figure 5.1b: Truck #2 (GFI)

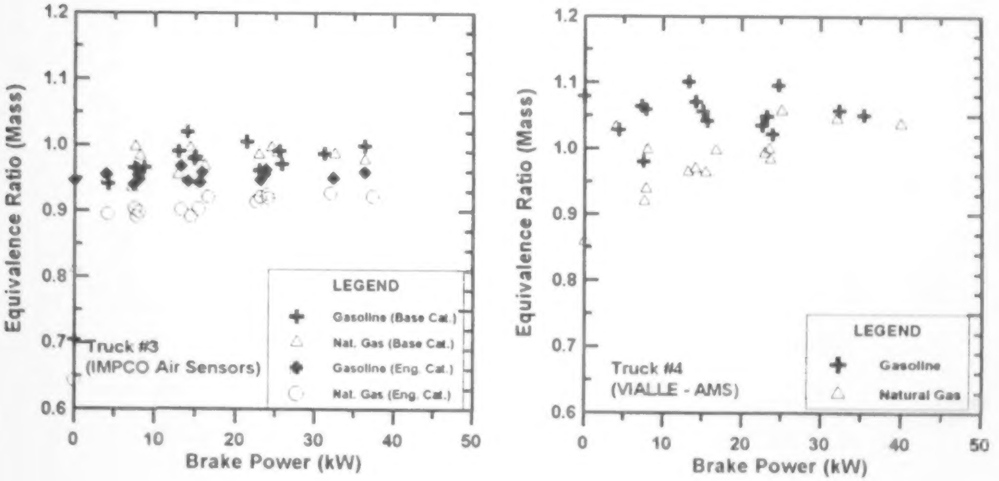

Figure 5.1c: Truck #3 (IMPCO)

Figure 5.1d: Truck #4 (VIALLE)

Figure 5.1: Air-Fuel Equivalence Ratio Results with Gasoline and Natural Gas Fuelling for the Various Trucks (Conversion Systems) at Part-Load (Multi-Modes)

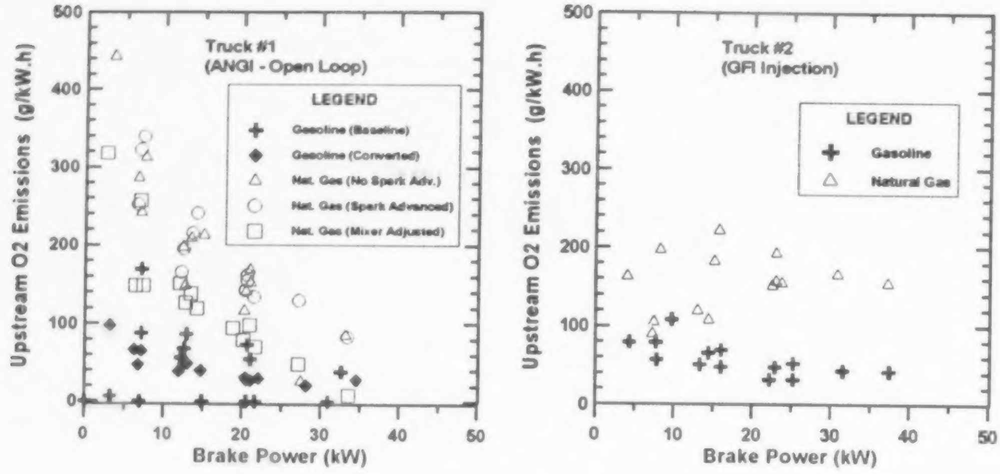

Figure 5.2a: Truck #1 (ANGI Open-Loop)

Figure 5.2b: Truck #2 (GFI)

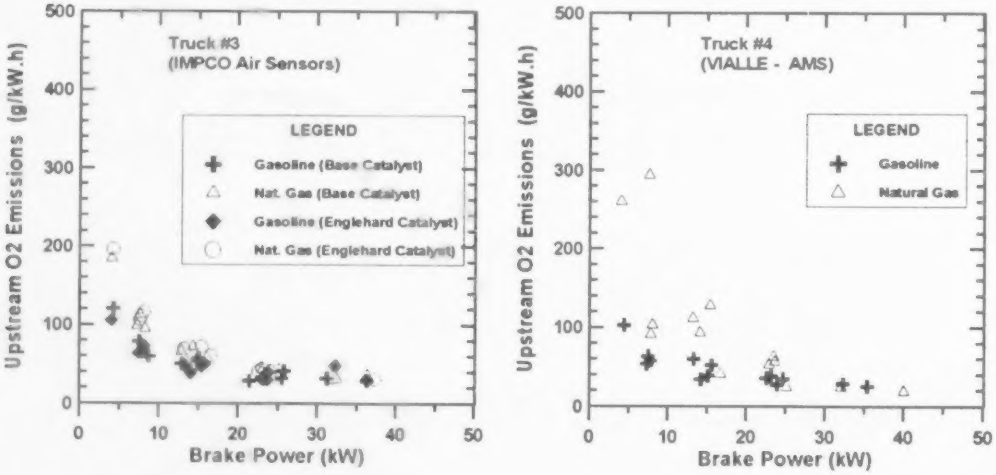

Figure 5.2c: Truck #3 (IMPCO)

Figure 5.2d: Truck #4 (VIALLE)

Figure 5.2: Engine-out Oxygen (O_2) Emission Results with Gasoline and Natural Gas Fuelling for the Various Trucks (Conversion Systems) at Part-Load (Multi-Modes)

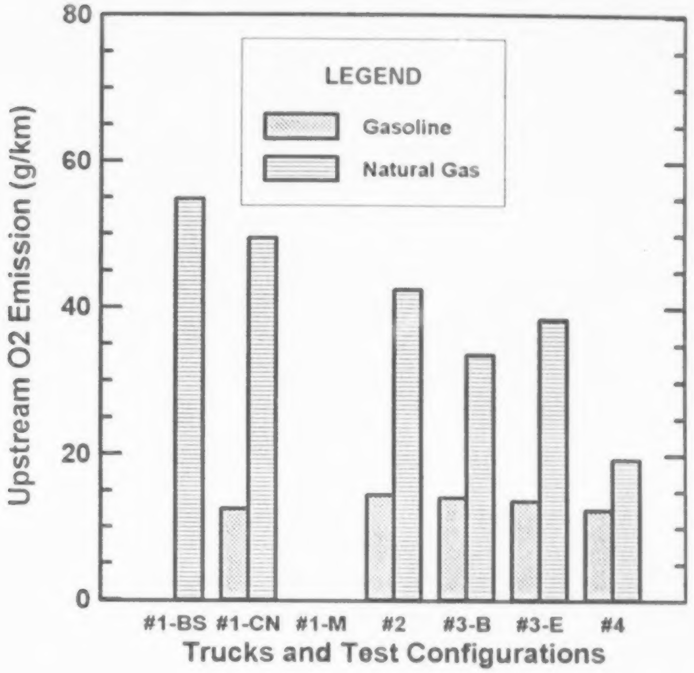

Figure 5.3: Comparison of the Composite Engine-out Oxygen (O_2) Results at Part-Load (Multi-Mode Tests)
Where:
#1-BS is Truck #1 (ANGI) "Baseline" (Gas.) and "Spark Advanced" (NG)
#1-CN is Truck #1 (ANGI) "Converted" (Gas.) and "No Spark Advanced" (NG)
#1-M is Truck #1 (ANGI) "Mixer Adjusted" (NG)
#2 is Truck #2 (GFI)
#3-B is Truck #3 (IMPCO) "Base Catalyst"
#3-E is Truck #3 (IMPCO) "Englehard Catalyst"
#4 is Truck #4 (VIALLE)

5.1.2 Fuel Consumption

Figures 5.4a, 5.4b, 5.4c and 5.4d show the corresponding plots of brake specific fuel consumption (b.s.f.c.) as a function of brake power for the four trucks operating on both gasoline and natural gas. A comparison of the composite fuel consumption results is given in figure 5.5. From the plots, it is evident that the b.s.f.c. decreased with increasing power. The brake specific fuel consumption was indefinite at idle since, though the engine consumed fuel, it produced no useful work for all the trucks on both gasoline and natural gas modes. The higher power modes (30 to 40 kW) gave a b.s.f.c. of about 350 g/kW.h. The decrease in b.s.f.c. with increasing power is due to the fact that the indicated mean effective pressure (i.m.e.p.) increased at a faster rate than the friction mean effective pressure (f.m.e.p.), so that the mechanical efficiency increased with power.

The composite fuel consumption on natural gas was lower than that on gasoline for every truck tested. For the gasoline operation, the composite fuel consumption rates ranged between 13.5 kg/100 km and 14.1 kg/100 km with an average value of 13.8 kg/100 km and a relative deviation of 1.59 %. The low variability between the fuel consumption rates for the various trucks on gasoline mode suggests that the addition of the conversion equipment had very little effect on the gasoline fuel consumption. On natural gas, for the trucks with closed-loop conversions, the composite fuel consumption rates ranged between 12.7 kg/100 km and 13.3 kg/100 km with a mean value of 13.1 kg/100 km and a relative deviation of 1.9 %. Truck #4 (VIALLE-AMS) gave the worst natural gas fuel consumption, probably because it ran rich on some modes.

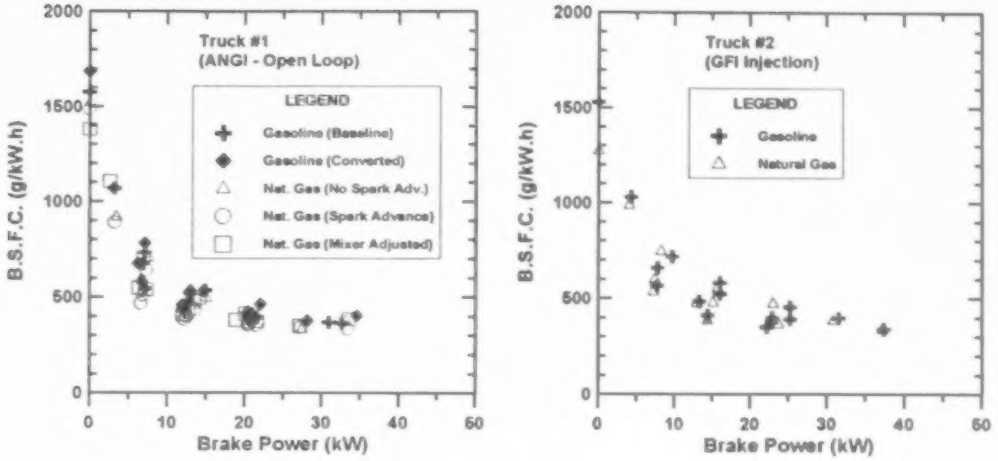

Figure 5.4a: Truck #1 (ANGI Open-Loop)

Figure 5.4b: Truck #2 (GFI)

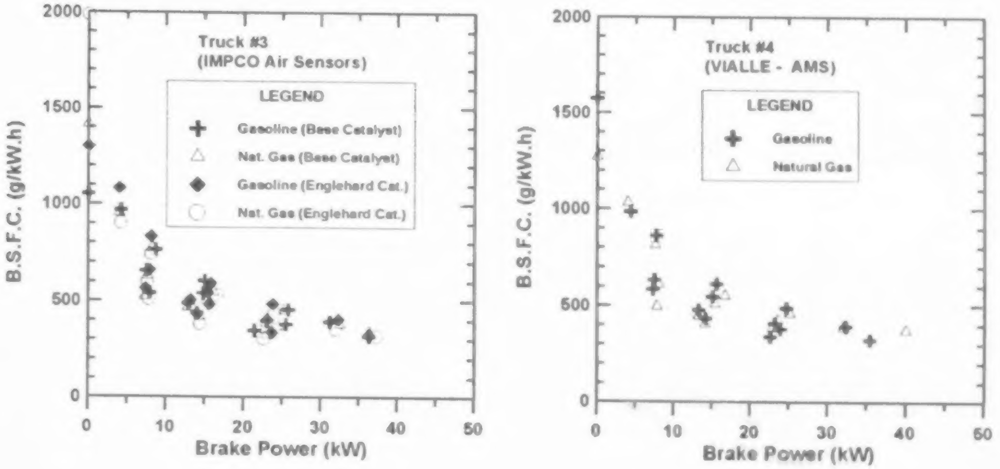

Figure 5.4: Truck #3 (IMPCO)

Figure 5.4d: Truck #4 (VIALLE)

Figure 5.4: Brake Specific Fuel Consumption (B.S.F.C.) with Gasoline and Natural Gas Fuelling for the Various Trucks (Conversion Systems) at Part-Load (Multi-Modes)

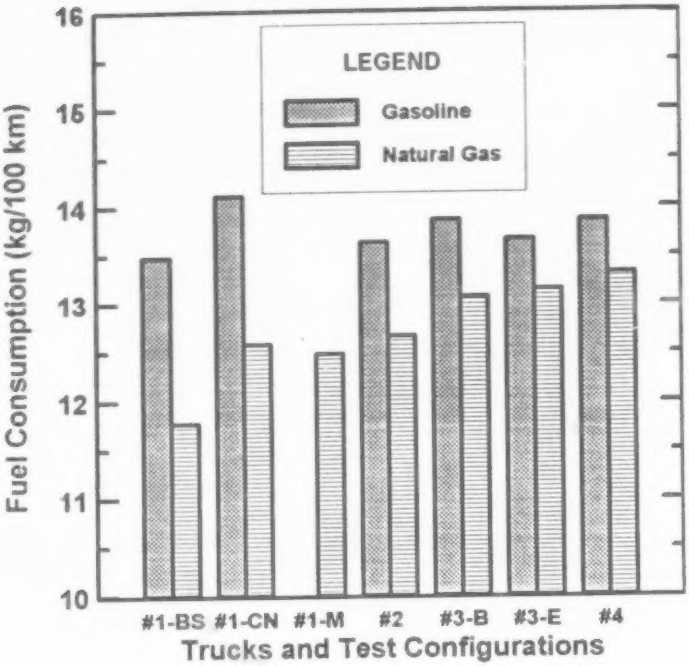

Figure 5.5: Comparison of the Composite Fuel Consumption Results at Part-Load (Multi-Mode Tests)
Where:
#1-BS is Truck #1 (ANGI) "Baseline" (Gas.) and "Spark Advanced" (NG)
#1-CN is Truck #1 (ANGI) "Converted" (Gas.) and "No Spark Advanced" (NG)
#1-M is Truck #1 (ANGI) "Mixer Adjusted" (NG)
#2 is Truck #2 (GFI)
#3-B is Truck #3 (IMPCO) "Base Catalyst"
#3-E is Truck #3 (IMPCO) "Englehard Catalyst"
#4 is Truck #4 (VIALLE)

The average natural gas fuel consumption was 5.10 % less than the average gasoline fuel consumption. The reduction in fuel consumption on natural gas is probably due to the fact that the lower heating value (LHV) of the gaseous fuel is higher (45.9 MJ/kg versus 43.5 MJ/kg). This correspounds to a 5.5 % increase in energy content compared to the 5.1 % reduction in fuel consumption.

The truck with the ANGI open-loop conversion consumed less fuel on natural gas than the other trucks due to its leaner operation (12.3 kg/100 km against 13.1 kg/100 km). The best fuel consumption on natural gas, about 8.5 % below the mean value, was achieved by truck #1 with the spark advanced. This fuel economy improvement could be entirely due to the improved combustion characteristics caused by the advanced ignition timing.

5.1.3 Carbon Dioxide (CO_2)

Generally, the brake specific carbon dioxide emissions had the same relationship with power as the brake specific fuel consumption. As more fuel is burnt, more CO_2 emissions are produced (for constant thermal efficiency), since only a trace of fuel carbon is emitted as carbon monoxide or hydrocarbons. Hence, like the b.s.f.c., the brake specific CO_2 emissions decreased with increasing power. The corresponding engine-out CO_2 emissions plots are shown in figures 5.6a, 5.6b, 5.6c, and 5.6d. From about 3000 g/kW.h for the low power modes, the CO_2 emissions decreased monotonically to about 1000 g/kW.h for the higher power modes. The plot of the composite CO_2 emissions is given in figure 5.7.

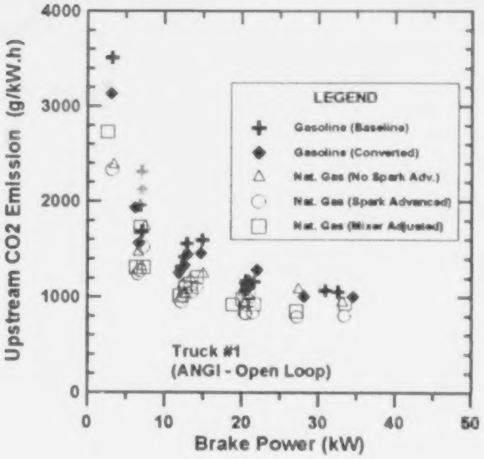

Figure 5.6a: Truck #1 (ANGI Open-Loop)

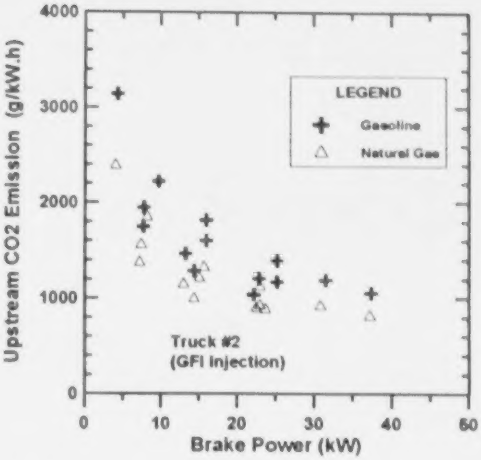

Figure 5.6b: Truck #2 (GFI)

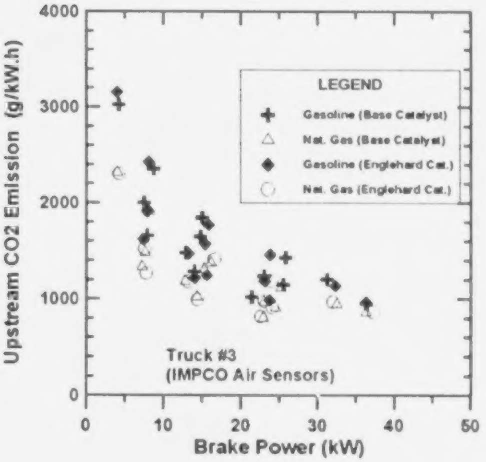

Figure 5.6c: Truck #3 (IMPCO)

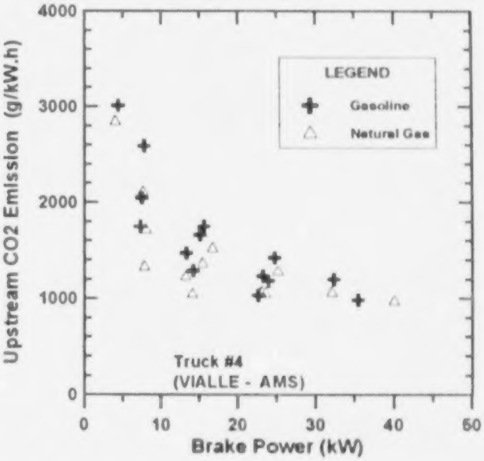

Figure 5.6d: Truck #4 (VIALLE)

Figure 5.6: Engine-out Carbon Dioxide (CO_2) Emission Results with Gasoline and Natural Gas Fuelling for the Various Trucks (Conversion Systems) at Part-Load (Multi-Modes)

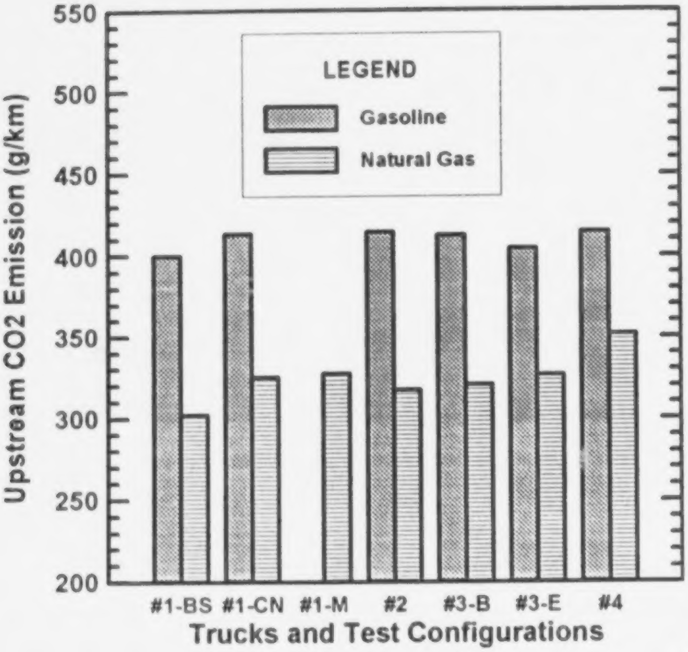

Figure 5.7: Comparison of the Composite Engine-out Carbon Dioxide (CO_2) Emission Results at Part-Load (Multi-ModeTests)

Where:

#1-BS is Truck #1 (ANGI) "Baseline" (Gas.) and "Spark Advanced" (NG)
#1-CN is Truck #1 (ANGI) "Converted" (Gas.) and "No Spark Advanced" (NG)
#1-M is Truck #1 (ANGI) "Mixer Adjusted" (NG)
#2 is Truck #2 (GFI)
#3-B is Truck #3 (IMPCO) "Base Catalyst"
#3-E is Truck #3 (IMPCO) "Englehard Catalyst"
#4 is Truck #4 (VIALLE)

The composite CO_2 emission values on gasoline ranged from 400 to 414 g/ km with a mean value of 410 g/km and a relative deviation of 1.46 %. On natural gas, as was the case for fuel consumption, the lowest CO_2 emissions were obtained from truck #1 (ANGI open-loop, with spark advanced), while the highest were obtained from truck #4 (VIALLE-AMS) which ran rich on some modes. The composite results for the trucks with closed-loop conversion systems ranged between 317 and 351 g/km with a mean value of 329 g/km and a relative deviation of 4.53 %. For the open-loop conversion, the composite CO_2 emissions was 325 g/km for normal operation, 327 g/km when the mixer was adjusted, and 302 g/km when the spark was advanced to compensate for the slower burning speed of natural gas.

The average reduction in the CO_2 emissions on natural gas was about 19.8 %. The reduction in the CO_2 emission on natural gas is due to two factors; lower carbon content by mass and lower fuel consumption. The natural gas used for the study contained about 70 to 75 % carbon by mass compared with about 85 % for gasoline, while the average composite fuel consumption on natural gas was 94.9 % of the gasoline value (13.1 versus 13.8 kg/100 km). These factors combine to predict reduced CO_2 emission of: 0.73 / 0.85 x 0.94 = 0.81. This is consistent with the ratio measured.

5.1.4 Oxides of Nitrogen (NOx)

a. Engine-out (Upstream) NOx Emissions

The brake specific engine-out oxides of nitrogen (NOx) emissions increased slightly with brake power, for both natural gas and gasoline operations for the trucks with closed-loop conversions. The absolute emission levels were more dependent on power, varying almost linearly with power. Figures 5.8a, 5.8b, 5.8c and 5.8d show the engine-out NOx emissions as functions of brake power for the various test configurations. The multi-mode composite upstream NOx emission results are compared in figure 5.9.

On gasoline, the NOx plots for the different truck configurations follow a similar pattern: NOx increasing with increase in brake power. This shows that the addition of the conversion equipment had little or no effect on the NOx emissions. The composite NOx emission results varied between 1.34 and 2.05 g/km with a mean value of 1.63 g/km and a relative deviation of 16.6 % between the vehicles. On natural gas, the composite NOx levels for the other trucks with feedback controlled conversions were also correspondingly lower than the emission levels produced while the trucks were fuelled by gasoline. This suggests that the conversions performed well. The composite NOx emission levels for these conversions on natural gas operations varied between 0.85 g/km and 1.18 g/km with a mean value of 1.05 g/km and a relative deviation of 13.3 %. There was greater variability between the three modes of truck #1 (ANGI open-loop) on natural gas. With the dual curve ignition system functioning (spark-advanced) the NOx level was quite high, 1.63 g/km on composite basis, because of the high spark advance employed. Without the system, the NOx level was 0.78 g/km, possibly implying retarded spark.

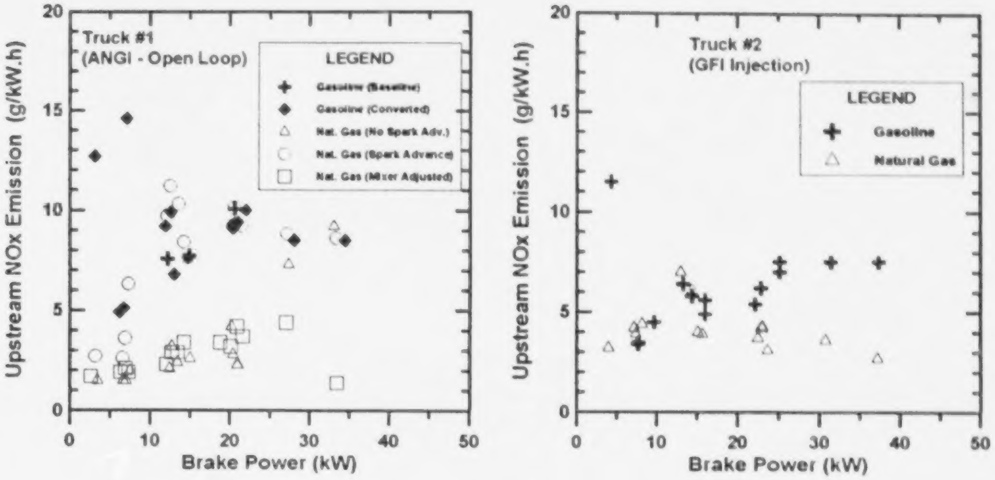

Figure 5.8a: Truck #1 (ANGI Open-Loop)

Figure 5.8b: Truck #2 (GFI)

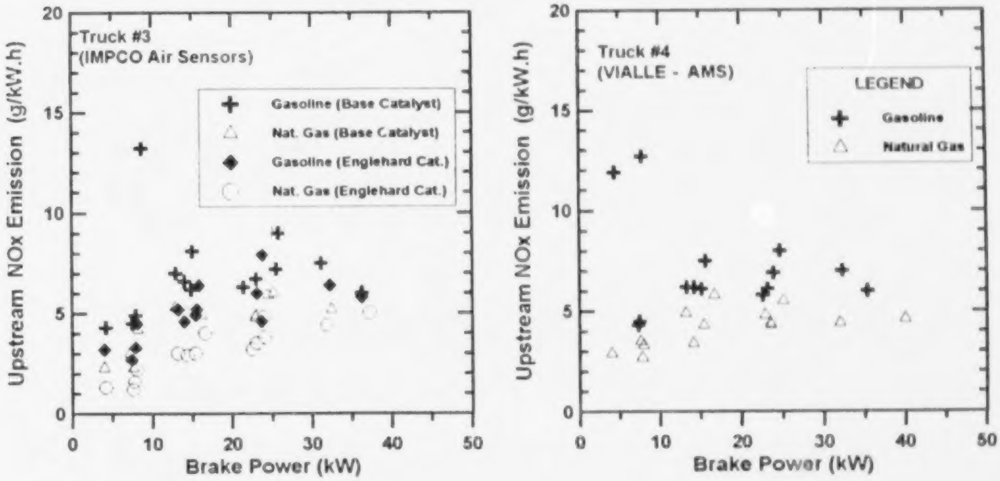

Figure 5.8c: Truck #3 (IMPCO)

Figure 5.8d: Truck #4 (VIALLE)

Figure 5.8: Engine-out Oxides of Nitrogen (NOx) Emission Results with Gasoline and Natural Gas Fuelling for the Various Trucks (Conversion Systems) at Part-Load (Multi-Modes)

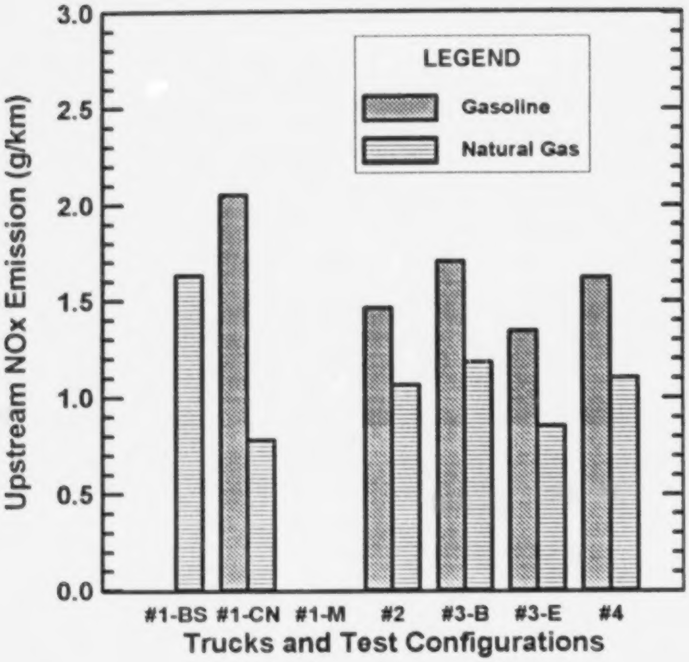

Figure 5.9: Comparison of the Composite Engine-out Oxides of Nitrogen (NOx) Emission Results at Part-Load (Multi-Mode Tests)

Where:

#1-BS is Truck #1 (ANGI) "Baseline" (Gas.) and "Spark Advanced" (NG)
#1-CN is Truck #1 (ANGI) "Converted" (Gas.) and "No Spark Advanced" (NG)
#1-M is Truck #1 (ANGI) "Mixer Adjusted" (NG)
#2 is Truck #2 (GFI)
#3-B is Truck #3 (IMPCO) "Base Catalyst"
#3-E is Truck #3 (IMPCO) "Englehard Catalyst"
#4 is Truck #4 (VIALLE)

The lower NOx levels on natural gas are due primarily to lower combustion temperatures (for stoichiometric mixtures in air at STP, the flame temperatures of methane is about 1875 °C compared to 2300 °C for gasoline [17]). In engines, this corresponds to slightly lower peak cylinder pressures with natural gas [13]. The same explanation is given from another perspective by Herrington and Shishu [13] who found that NO emissions at a given fuel-air equivalence ratio were strongly dependent on the fuel hydrogen-to carbon ratio, with high values of H/C giving lower NO emissions.

b. Tailpipe (Downstream) NOx Emissions

Like the engine-out emissions, the tailpipe specific NOx emissions on natural gas had no clear relationship with brake power. Figures 5.10a, 5.10b, 5.10c and 5.10d show plots of the tailpipe NOx emissions against brake power, while Figure 5.11 shows a plot of the composite tailpipe emissions.

There was significant truck-to-truck variability in the composite tailpipe NOx emissions for both fuels. On gasoline, the lowest composite NOx emissions of 0.04 g/km was produced by truck #1 (baseline). This value is significantly lower than those obtained from other trucks thus suggesting that some error may have been committed during the first series of tests. The error may have resulted from faulty calibration of the gas analyzers or some of the other test equipment. For the other trucks on gasoline modes, the NOx emissions ranged between 0.23 and 0.60 g/km with a mean value of 0.35 g/km and a relative deviation of 45.7 %. On natural gas, for the closed-loop conversions, the composite NOx emissions ranged between 0.20 and 0.83 g/km with a tailpipe NOx emissions of 1.04 g/km on natural gas.

It is evident that the trucks produced higher tailpipe NOx emissions on natural gas, even though the engine-out emissions were lower. These higher values obtained on natural gas were due to low catalyst conversion efficiency. Figure 5.12 shows a plot of the composite NOx conversion efficiency. The composite efficiency on gasoline ranged from 64.7 % to 87.8 % with a mean value of 78.1%. On natural gas, the efficiency ranged from 24.6 % for truck #4 (VIALLE-AMS) to 76.5 % for truck #3 (IMPCO-Englehard Catalyst) with a mean value of 51.2 %. The average efficiency for the ANGI open-loop conversion was 24.5 %. This reduction in NOx efficiency on natural gas was due to less precise mixture control combined with insufficient amount of CO in the raw exhaust to promote NOx reduction. The worst cases were trucks #1 and #3 which tended to run lean on high power modes thus eliminating the action of the 3-way catalyst in the worst NOx production modes. Truck #1 especially gave very high tailpipe emissions because of the high engine-out emissions and the very low conversion efficiency resulting from the lean operation for the high power modes.

The reduced catalyst effectiveness on natural gas could also be marginally affected by reduced catalyst temperature. The readings of temperature sensors placed upstream of the catalytic converters showed the average value for the gasoline operations was 505 °C (± 3 °C), while the value for the natural gas operations was 500 °C (± 2 °C). Figure 5.13a, 5.13b, 5.13c and 5.13d show the variation of the temperature values with brake power.

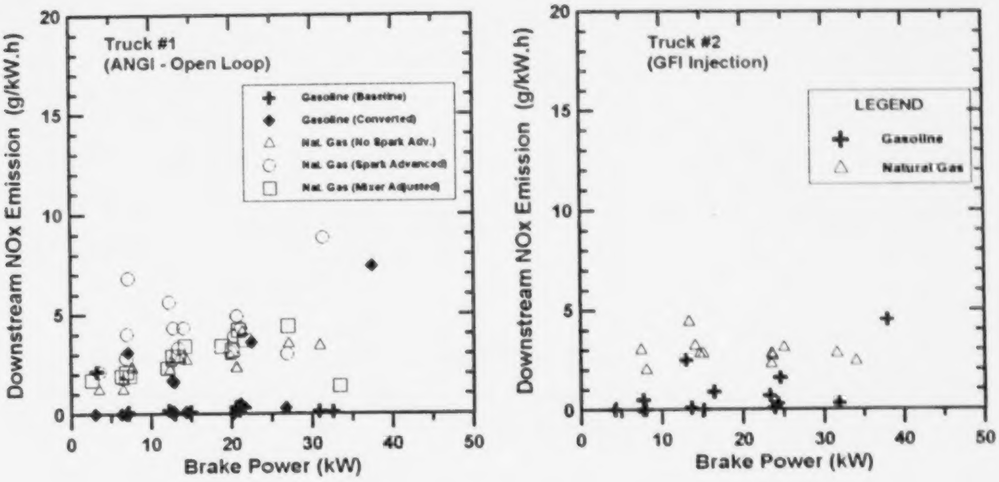

Figure 5.10a: Truck #1 (ANGI Open-Loop) **Figure 5.10b:** Truck #2 (GFI)

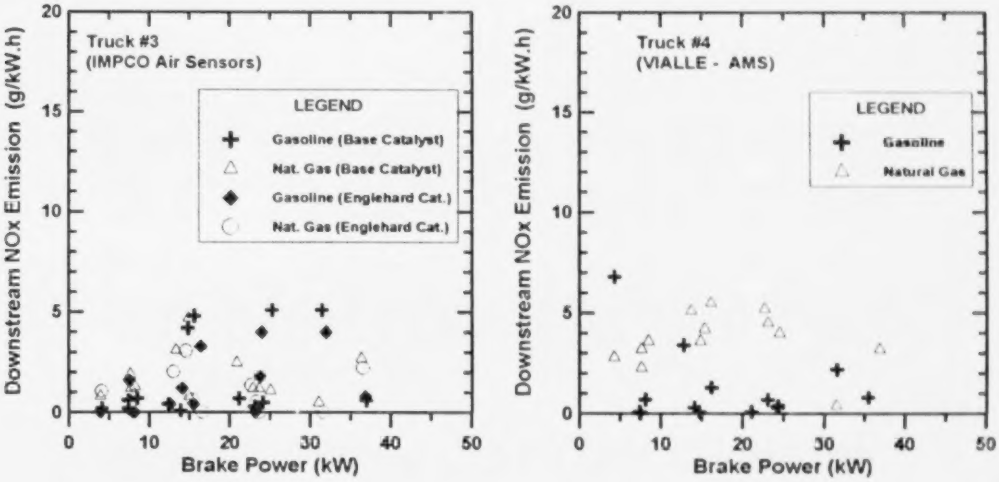

Figure 5.10c: Truck #3 (IMPCO) **Figure 5.10d:** Truck #4 (VIALLE)

Figure 5.10: Tailpipe Oxides of Nitrogen (NOx) Emission Results with Gasoline and Natural Gas Fuelling for the Various Trucks (Conversion Systems) at Part-Load (Multi-Modes)

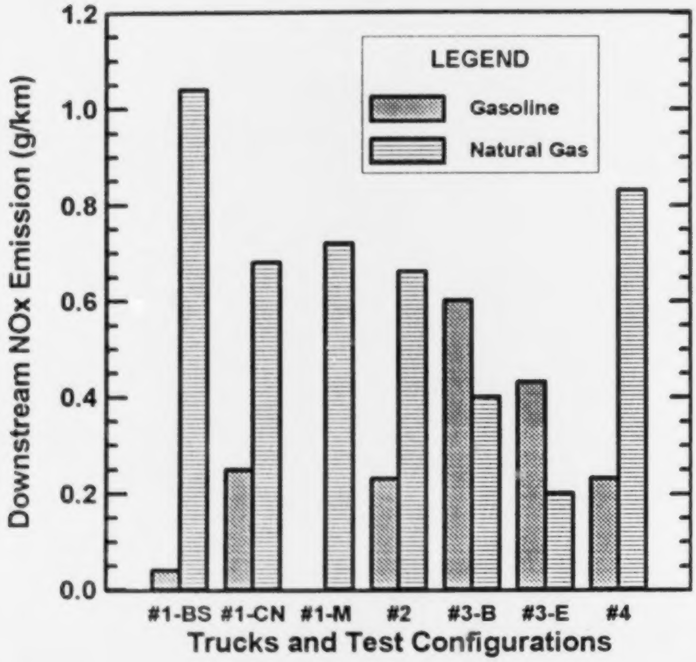

Figure 5.11: Comparison of the Composite Tailpipe Oxides of Nitrogen (NOx) Emission Results at Part-Load (Multi-Mode Tests)
Where:
#1-BS is Truck #1 (ANGI) "Baseline" (Gas.) and "Spark Advanced" (NG)
#1-CN is Truck #1 (ANGI) "Converted" (Gas.) and "No Spark Advanced" (NG)
#1-M is Truck #1 (ANGI) "Mixer Adjusted" (NG)
#2 is Truck #2 (GFI)
#3-B is Truck #3 (IMPCO) "Base Catalyst"
#3-E is Truck #3 (IMPCO) "Englehard Catalyst"
#4 is Truck #4 (VIALLE)

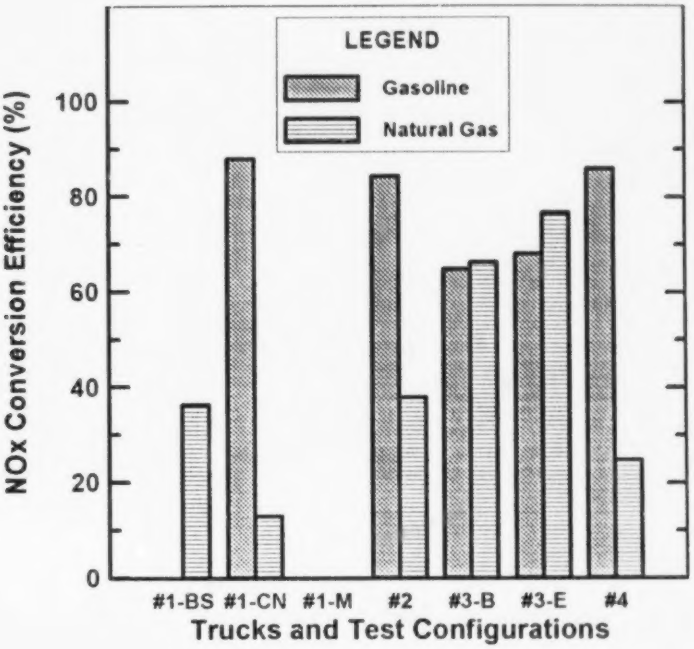

Figure 5.12: Comparison of the Composite Oxides of Nitrogen (NOx) Catalyst Efficiency Results at Part-Load (Multi-Mode Tests)

Where:

#1-BS is Truck #1 (ANGI) "Baseline" (Gas.) and "Spark Advanced" (NG)
#1-CN is Truck #1 (ANGI) "Converted" (Gas.) and "No Spark Advanced" (NG)
#1-M is Truck #1 (ANGI) "Mixer Adjusted" (NG)
#2 is Truck #2 (GFI)
#3-B is Truck #3 (IMPCO) "Base Catalyst"
#3-E is Truck #3 (IMPCO) "Englehard Catalyst"
#4 is Truck #4 (VIALLE)

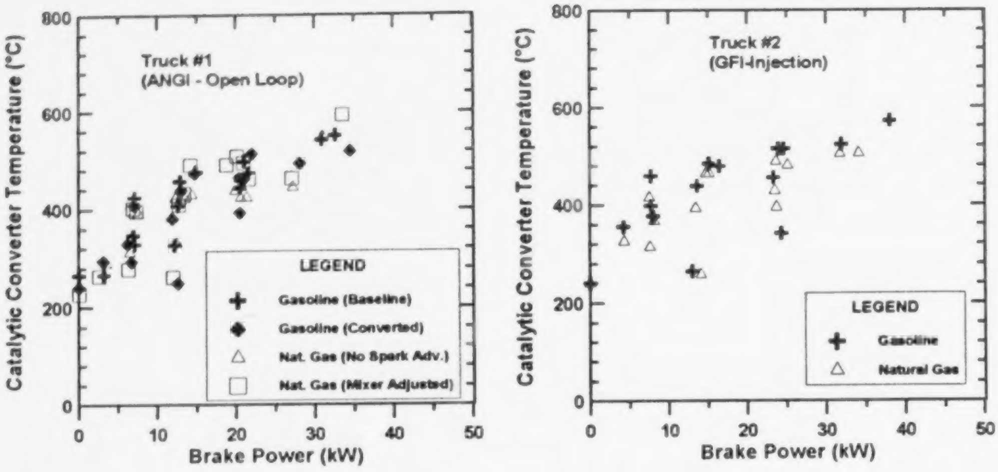

Figure 5.13a: Truck #1 (ANGI Open-Loop)

Figure 5.13b: Truck #2 (GFI)

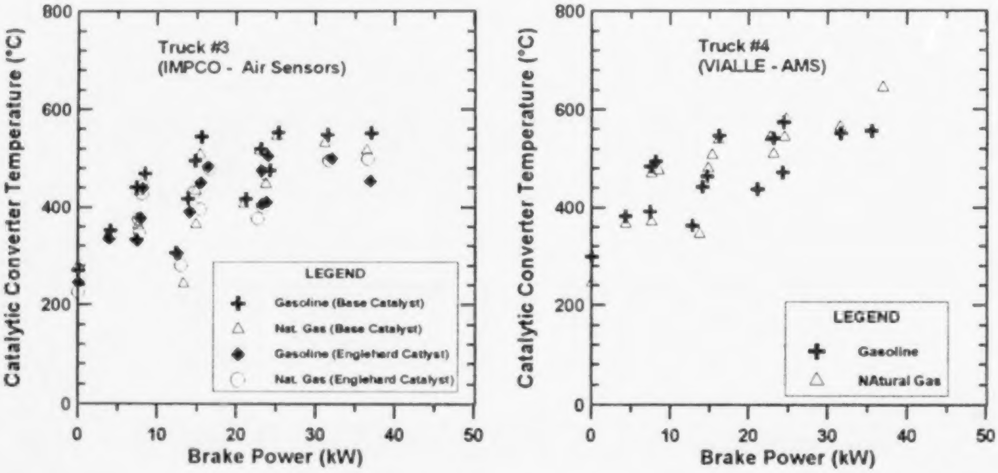

Figure 5.13c: Truck #3 (IMPCO)

Figure 5.13d: Truck #4 (VIALLE)

Figure 5.13: Catalytic Converter Temperature Results with Gasoline and Natural Gas Fuelling for the Various Trucks (Conversion Systems) at Part-Load (Multi-Modes)

5.1.5 Carbon Monoxide (CO)

a. Engine-out (Upstream) CO Emissions

It is well known that CO emissions are primarily a function of the equivalence ratio, with an approximately linear increase as the ratio is increased on the rich side of stoichiometric. However, variation in the equivalence ratio for each trucks was too small to establish a definite relationship between the two quantities. Therefore, it is not surprising that the brake specific CO emissions in the raw exhaust (upstream of the catalyst) had no definite relationship with brake power for both gasoline and natural gas operations. However, the absolute emission levels increased slightly with brake power. This could be attributed to an increase in burnt mixtures trapped in ring grooves and cylinder crevices with increased cylinder pressure. The plots of the engine-out CO emissions as functions of brake power are shown in figures 5.14a, 5.14b, 5.14c and 5.14d. Figure 5.15 shows a comparison of the composite engine-out CO emissions.

On gasoline, the composite engine-out CO emissions with a mean value of 9.56 g/km and a standard deviation of 1.68 g/km (17.6%) and ranged from 7.98 to 11.4 g/km. For the trucks with closed-loop conversions, on natural gas, the composite emission results ranged from a low of 3.64 g/km for truck #4 (VIALLE-AMS) to 11.54 g/km for truck #2 (GFI-Injection) with a mean value of 8.58 g/km and a relative deviation of 40 %. The production of high CO emissions by the GFI and IMPCO was because the trucks ran slightly richer on some modes than the other trucks. Truck #1 with open-loop conversion produced low CO emissions on natural gas (average value of 2.34 g/km) because of its lean operation.

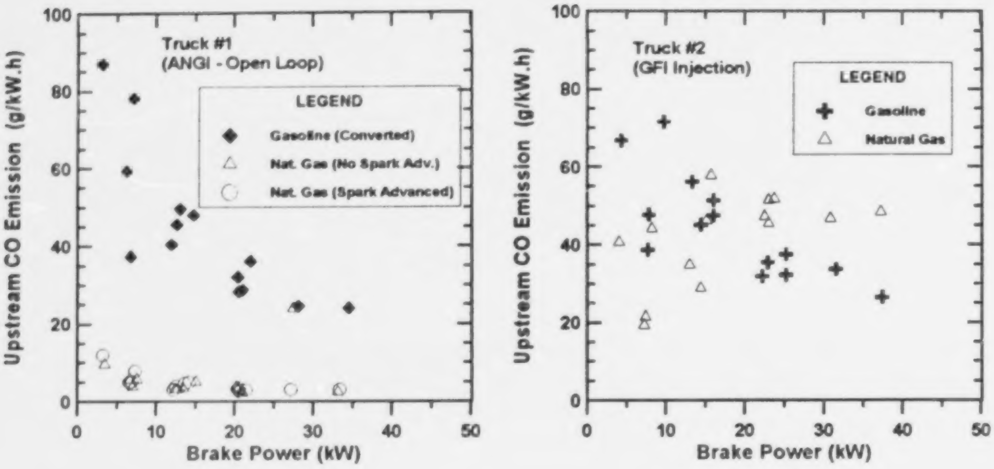

Figure 5.14a: Truck #1 (ANGI Open-Loop)

Figure 5.14b: Truck #2 (GFI)

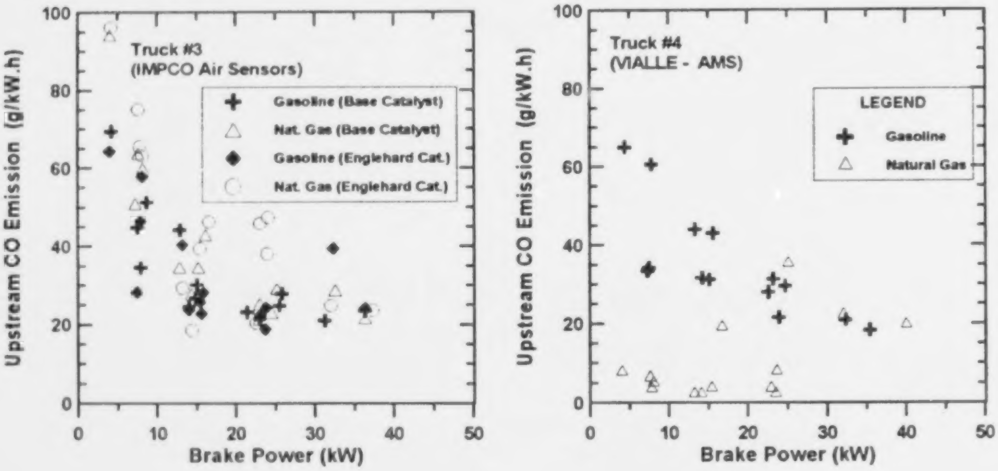

Figure 5.14c: Truck #3 (IMPCO)

Figure 5.14d: Truck #4 (VIALLE)

Figure 5.14: Engine-out Carbon Monoxide (CO) Emission Results with Gasoline and Natural Gas Fuelling for the Various Trucks (Conversion Systems) at Part-Load (Multi-Modes)

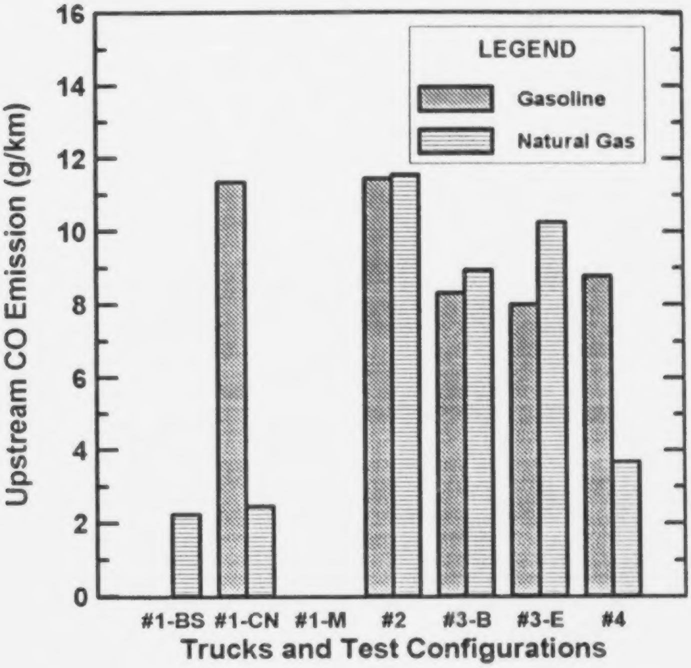

Figure 5.15: Comparison of the Composite Engine-out Carbon Monoxide (CO) Emission Results at Part-Load (Multi-Mode Tests)
Where:
#1-BS is Truck #1 (ANGI) "Baseline" (Gas.) and "Spark Advanced" (NG)
#1-CN is Truck #1 (ANGI) "Converted" (Gas.) and "No Spark Advanced" (NG)
#1-M is Truck #1 (ANGI) "Mixer Adjusted" (NG)
#2 is Truck #2 (GFI)
#3-B is Truck #3 (IMPCO) "Base Catalyst"
#3-E is Truck #3 (IMPCO) "Englehard Catalyst"
#4 is Truck #4 (VIALLE)

It is evident that the trucks ran cleaner, with respect to CO, on natural gas than on gasoline. The lower emissions on natural gas is due to its gaseous nature which helps to ensure adequate mixing of fuel and air. The lower carbon content and the leaner operations on natural gas may have also contributed to the lower CO values.

b. Tailpipe (Downstream) CO Emissions

Like the engine-out emissions, the tailpipe CO emissions had no definite relationship with brake power, though the tailpipe figures were much lower. The plots of the tailpipe CO emissions as functions of brake power are shown in figures 5.16a, 5.16b, 5.16c and 5.16d. The composite results are plotted in figure 5.17. On gasoline, the composite emission values ranged between 0.21 g/km and 0.90 g/km with a mean value of 0.54 g/km and a relative deviation of 53.7 %. On natural gas, for the trucks with closed-loop conversion, the composite tailpipe CO emissions varied between 0.21 g/km for truck #2 (GFI-Injection) and 1.13 g/km for #3 (IMPCO-Air Sensors) with a mean value of 0.61 g/km and a relative deviation of 63.9 %. Though significant differences exist between the various conversions, the emission levels were generally low. For the open-loop conversion (ANGI), the mean emission was a very low 0.25 g/km.

Generally, the tailpipe CO emissions were very low because of the high catalyst conversion efficiencies. On gasoline the average CO conversion efficiency was 95.4 %, while on natural gas it was 91.8%. The slightly reduced catalyst effectiveness on natural gas could be attributed to less precise mixture control. High CO could be produced on some rich running modes and, hence, the catalyst cannot effectively oxidize the CO.

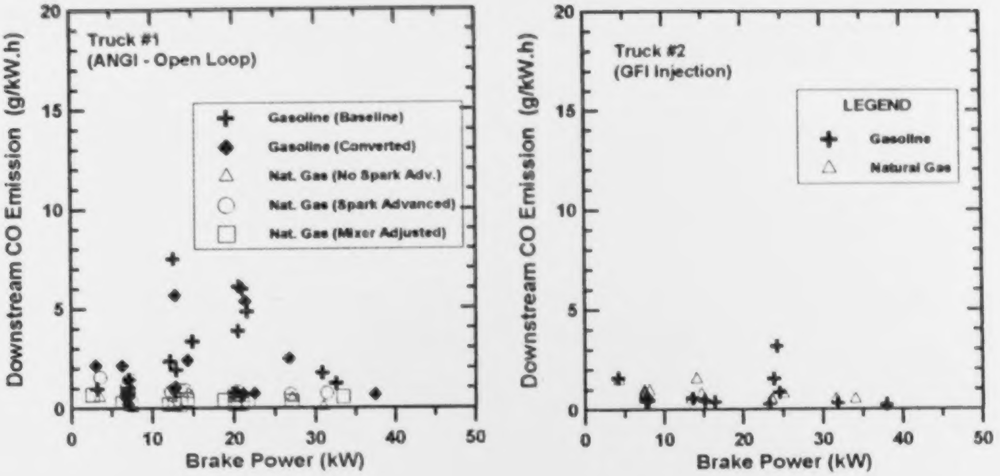

Figure 5.16a: Truck #1 (ANGI Open-Loop)

Figure 5.16b: Truck #2 (GFI)

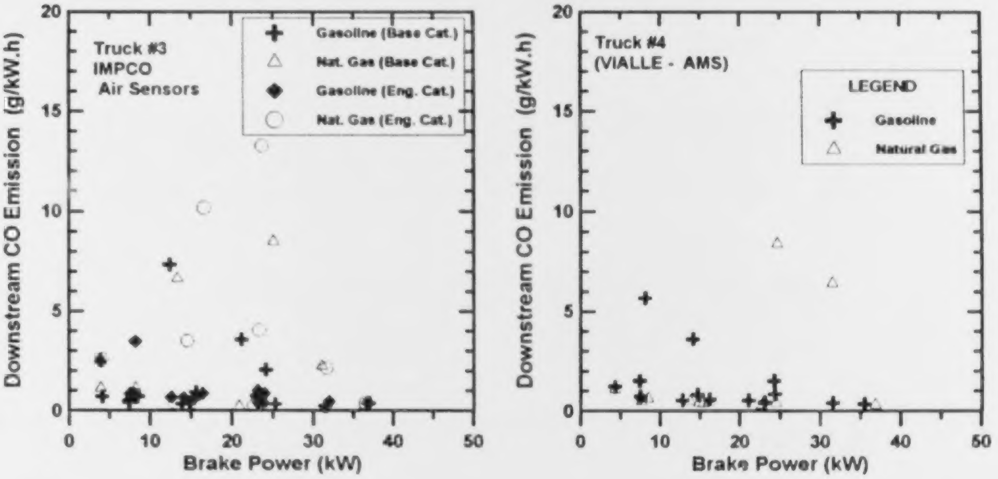

Figure 5.16c: Truck #3 (IMPCO)

Figure 5.16d: Truck #4 (VIALLE)

Figure 5.16: Tailpipe Carbon Monoxide (CO) Emission Results with Gasoline and Natural Gas Fuelling for the Various Trucks (Conversion Systems) at Part-Load (Multi-Modes)

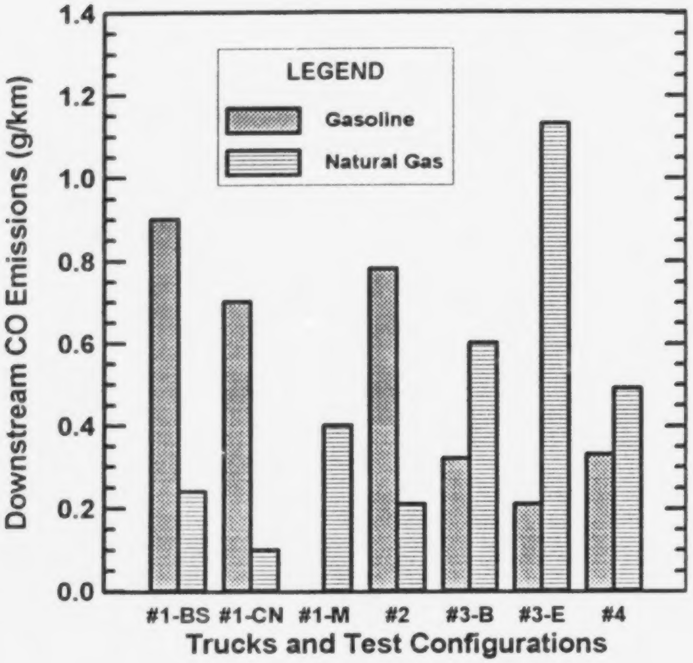

Figure 5.17: Comparison of the Composite Tailpipe Carbon Monoxide (CO) Emission Results at Part-Load (Multi-Mode Tests)

Where:

#1-BS is Truck #1 (ANGI) "Baseline" (Gas.) and "Spark Advanced" (NG)
#1-CN is Truck #1 (ANGI) "Converted" (Gas.) and "No Spark Advanced" (NG)
#1-M is Truck #1 (ANGI) "Mixer Adjusted" (NG)
#2 is Truck #2 (GFI)
#3-B is Truck #3 (IMPCO) "Base Catalyst"
#3-E is Truck #3 (IMPCO) "Englehard Catalyst"
#4 is Truck #4 (VIALLE)

5.1.6 Reactive Non-Methane Hydrocarbons (RHC)

a. Engine-out (Upstream) RHC Emissions

The brake specific engine-out RHC emissions were found to be very dependent on brake power for the gasoline operations, whereas no clear relationship could be determined between the two quantities for the natural gas operations. On gasoline, the specific emissions were found to decrease with increasing brake power. On natural gas, the brake specific emissions were much lower and were independent of power. However, the absolute emission values increased with power. The corresponding plots of engine-out RHC emissions as functions of brake power are shown in figures 5.18a, 5.18b, 5.18c and 5.18d., while a comparison of the composite results is given in figure 5.19.

On gasoline, the mean composite emission value was 1.39 g/km with a range of 1.00 to 1.71 g/km and a standard deviation of 0.26 (18.70 %). On natural gas, for the trucks with closed-loop conversions, the composite values ranged between 0.15 g/km (GFI-injection) and 0.36 g/km (VIALLE-AMS) with a mean value of 0.26 g/km and a standard deviation of 42.5 %. The high value of RHC emission produced by truck #4 which had the VIALLE-AMS conversion system was due to the richer operation in some modes than the other trucks. Truck #1 (ANGI open-loop) produced very low RHC emissions (average of 0.10 g/km). This is probably due to the lean operation in most of the modes.

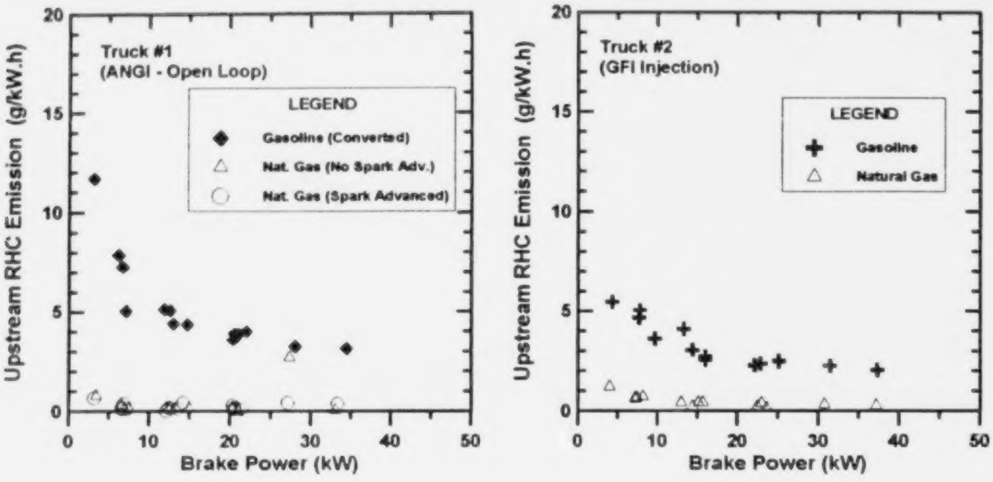

Figure 5.18a: Truck #1 (ANGI Open-Loop)

Figure 5.18b: Truck #2 (GFI)

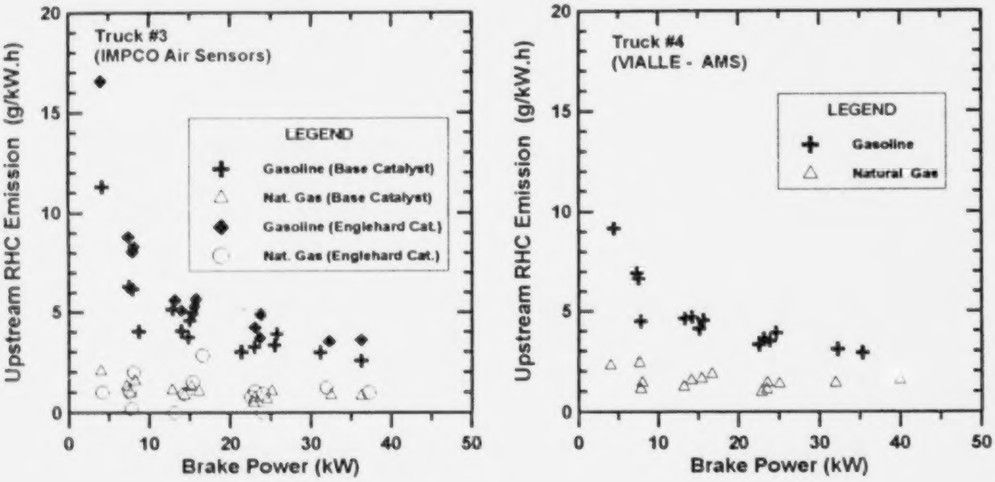

Figure 5.18c: Truck #3 (IMPCO)

Figure 5.18d: Truck #4 (VIALLE)

Figure 5.18: Engine-out Reactive Non-Methane Hydrocarbons (RHC) Emission Results with Gasoline and Natural Gas Fuelling for the Various Trucks (Conversion Systems) at Part-Load (Multi-Modes)

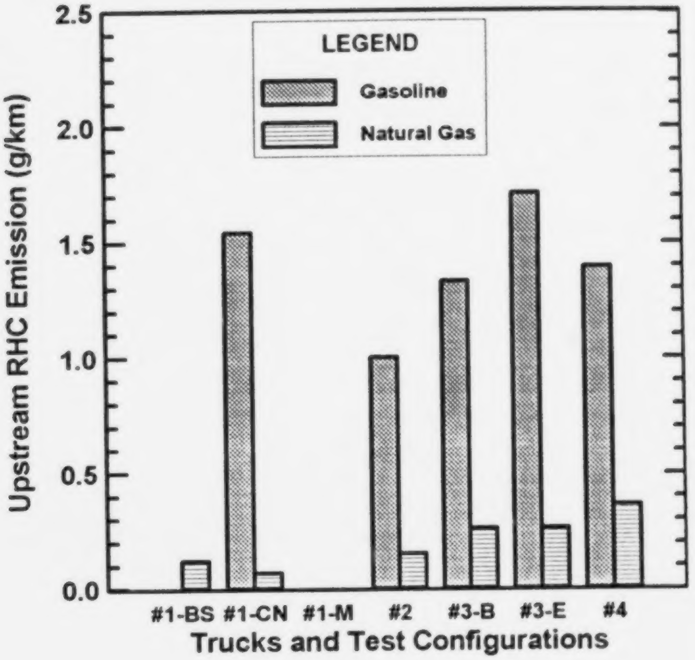

Figure 5.19: Comparison of the Composite Engine-out Reactive Non-Methane Hydrocarbons (RHC) Emission Results at Part-Load (Multi-Mode Tests)
Where:
#1-BS is Truck #1 (ANGI) "Baseline" (Gas.) and "Spark Advanced" (NG)
#1-CN is Truck #1 (ANGI) "Converted" (Gas.) and "No Spark Advanced" (NG)
#1-M is Truck #1 (ANGI) "Mixer Adjusted" (NG)
#2 is Truck #2 (GFI)
#3-B is Truck #3 (IMPCO) "Base Catalyst"
#3-E is Truck #3 (IMPCO) "Englehard Catalyst"
#4 is Truck #4 (VIALLE)

The engine-out RHC emissions were, on average, 81.3 % lower on natural gas. The lower engine-out emissions of RHC on natural gas is primarily because most of the fuel and, hence most of the hydrocarbon emissions were, in the form of non-reactive methane hydrocarbons. The reduction is also due to the gaseous nature of the gas which helps to ensure better mixing of the fuel and air and, therefore, more complete combustion.

b. Tailpipe (Downstream) RHC Emissions

No clear relationship could be established between the brake specific tailpipe reactive non-methane hydrocarbons (RHC) and the brake power. However, the emission levels were much lower than the engine-out emission levels, especially for gasoline operations due to the high catalyst efficiency. The corresponding plots of the tailpipe RHC emissions as functions of brake power are presented in figures 5.20a, 5.20b, 5.20c and 5.20d, while a comparison of the composite values is given in figure 5.21.

On gasoline the composite emission values ranged between 0.09 g/km and 0.20 with a mean value of 0.15 g/km and a relative deviation of 33.3 %. On natural gas, the trucks with closed-loop conversion had a mean composite emission value of 0.16 g/km with a range of 0.07 g/km (GFI-injection) to 0.26 g/km (VIALLE-AMS) and a relative deviation of 50 %. Though differences exist between the emissions from the trucks using different natural gas conversion systems, the emission levels were generally low (about 40 % lower than on gasoline).

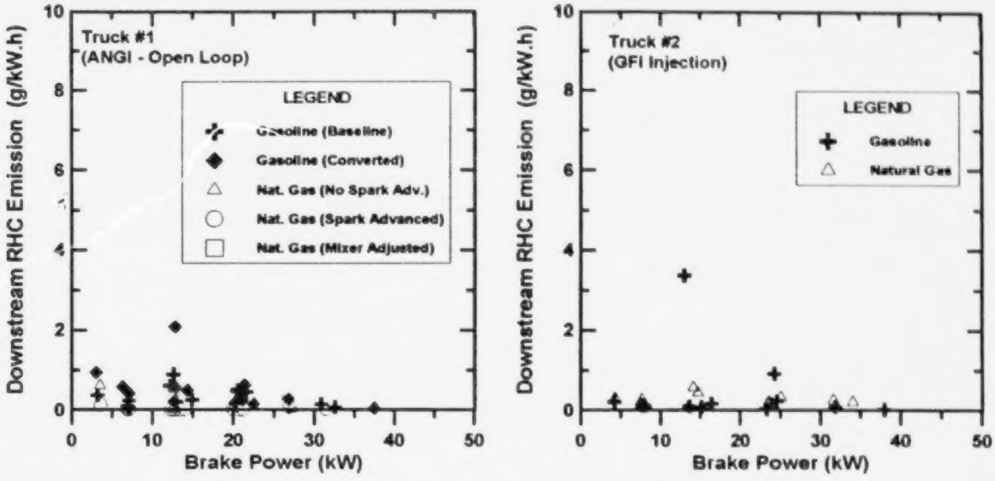

Figure 5.20a: Truck #1 (ANGI Open-Loop)

Figure 5.20b: Truck #2 (GFI)

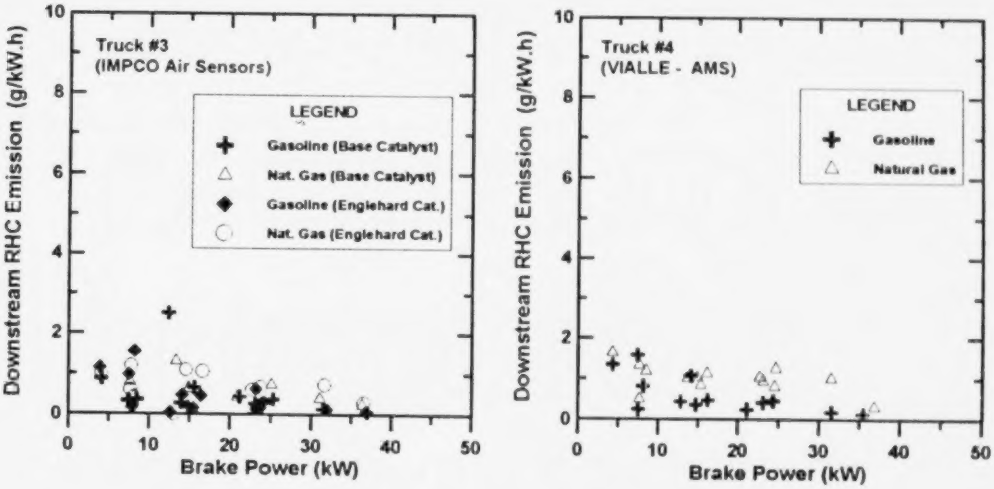

Figure 5.20c: Truck #3 (IMPCO)

Figure 5.20d: Truck #4 (VIALLE)

Figure 5.20: Tailpipe Reactive Non-Methane Hydrocarbons (RHC) Emission Results with Gasoline and Natural Gas Fuelling for the Various Trucks (Conversion Systems) at Part-Load (Multi-Modes)

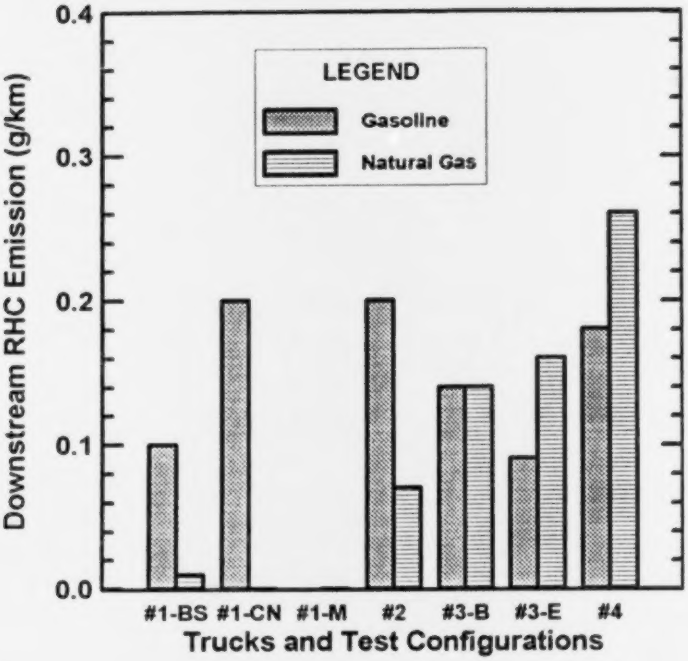

Figure 5.21: Comparison of the Composite Tailpipe Reactive Non-Methane Hydrocarbons (RHC) Emission Results at Part-Load (Multi-Mode Tests)
Where:
#1-BS is Truck #1 (ANGI) "Baseline" (Gas.) and "Spark Advanced" (NG)
#1-CN is Truck #1 (ANGI) "Converted" (Gas.) and "No Spark Advanced" (NG)
#1-M is Truck #1 (ANGI) "Mixer Adjusted" (NG)
#2 is Truck #2 (GFI)
#3-B is Truck #3 (IMPCO) "Base Catalyst"
#3-E is Truck #3 (IMPCO) "Englehard Catalyst"
#4 is Truck #4 (VIALLE)

The tailpipe emissions on natural gas were not as reduced (compared to gasoline), as the engine-out emissions because of the reduced catalyst effectiveness. The average catalyst conversion efficiency on gasoline was found to be 87.7 %, with a range of 80.0 to 94.7 %, while on natural gas, for the closed-loop conversions, the mean value was 41.5 % with a range of 27.8 % to 53.3 %.

5.1.7 Methane - Non Reactive Hydrocarbons (CH_4)

a. Engine-out (Upstream) CH_4 Emissions

On gasoline, the trucks produced only negligible amounts of CH_4 (this could not be detected in many tests). On natural gas, however, the engine-out brake specific methane hydrocarbon, CH_4, emissions were found to decrease with increasing brake power (though they tended to increase with power on absolute basis). The plots of the engine-out CH_4 emissions as functions of power are shown in figures 5.22a, 5.22b, 5.22c and 5.22d., while a comparison of the composite emission values is shown in figure 5.23.

For the trucks fitted with the closed-loop conversion systems, the composite values had a mean value of 1.00 g/km with a range of 0.39 to 1.32 g/km and a standard deviation of 0.43 (43 %). The emission levels were generally low. The average emission from the truck with the open-loop system was 1.02 g/km (about 0.7 % of the 131 g/km fuel consumption on natural gas).

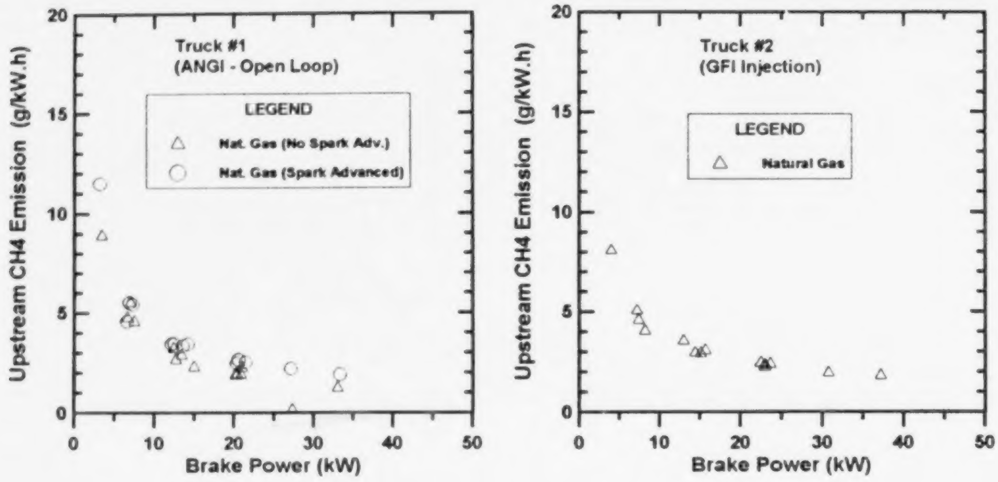

Figure 5.22a: Truck #1 (ANGI Open-Loop)

Figure 5.22b: Truck #2 (GFI)

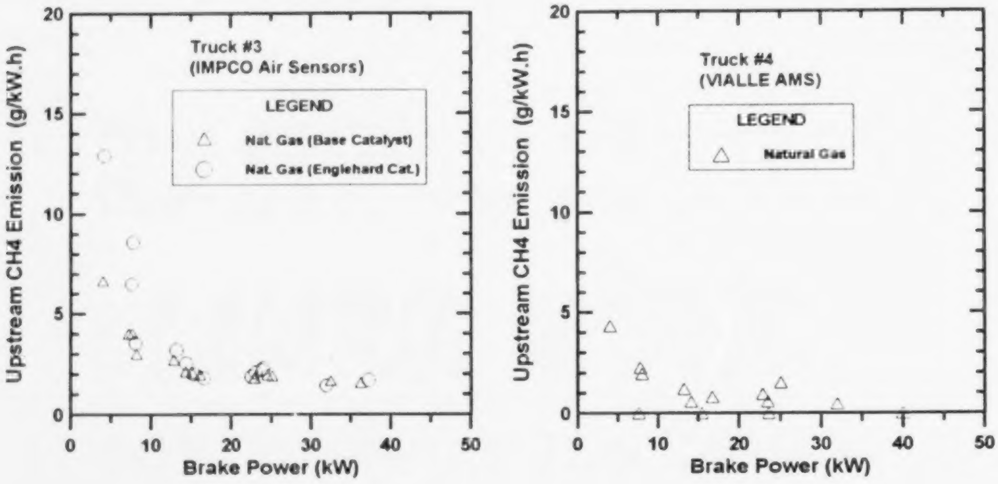

Figure 5.22c: Truck #3 (IMPCO)

Figure 5.22d: Truck #4 (VIALLE)

Figure 5.22: Engine-out Methane Hydrocarbons (CH_4) Emission Results with Gasoline and Natural Gas Fuelling for the Various Trucks (Conversion Systems) at Part-Load (Multi-Modes)

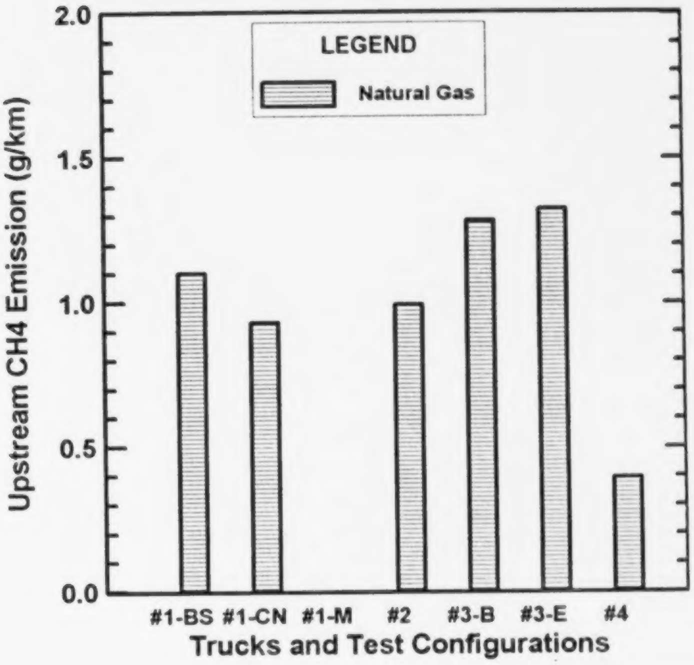

Figure 5.23: Comparison of the Composite Engine-out Methane Hydrocarbons (CH_4) Emission Results at Part-Load (Multi-Mode Tests)
Where:
#1-BS is Truck #1 (ANGI) "Baseline" (Gas.) and "Spark Advanced" (NG)
#1-CN is Truck #1 (ANGI) "Converted" (Gas.) and "No Spark Advanced" (NG)
#1-M is Truck #1 (ANGI) "Mixer Adjusted" (NG)
#2 is Truck #2 (GFI)
#3-B is Truck #3 (IMPCO) "Base Catalyst"
#3-E is Truck #3 (IMPCO) "Englehard Catalyst"
#4 is Truck #4 (VIALLE)

b. Tailpipe (Downstream) CH_4 Emissions

As in the upstream of catalyst case, the tailpipe methane hydrocarbons emissions were negligible on gasoline. On natural gas, the brake specific CH_4 emissions decreased with increasing brake power. Figures 5.24a, 5.24b, 5.24c and 5.24d show the plots of the tailpipe CH_4 emissions as functions of brake power, and figure 5.25 shows the corresponding composite values.

The composite emission values, for the closed-loop conversions, ranged between 0.04 and 0.43 g/km with a mean value of 0.21 g/km and a standard deviation of (81 %). These emission values were generally, very low because of the precise mixture control which led to high catalytic conversion efficiency. On the other hand, the CH_4 emissions from truck #1 (ANGI open-loop) were high due to the lack of feedback control. The truck would, therefore, periodically run rich, thereby producing high methane while reducing the effectiveness of the catalytic converter. The composite tailpipe emission from this truck was 0.86 g/km.

The mean methane conversion efficiencies for the closed-loop systems ranged between 46.2 % for truck #4 (VIALLE-AMS) and 97.0 % for truck #3 (IMPCO-Air Sensors) with a mean value of 73.9 %. The efficiencies for truck #1, which operated on open-loop, were particularly low because of poor mixture control which reduced the catalyst effectiveness. The average CH_4 conversion efficiency for this truck was only 11.3 %.

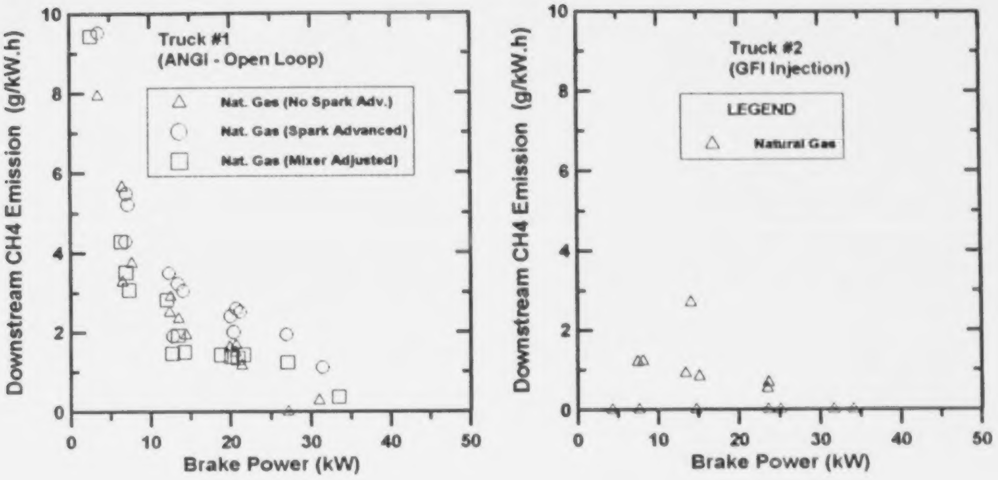

Figure 5.24a: Truck #1 (ANGI Open-Loop)

Figure 5.24b: Truck #2 (GFI)

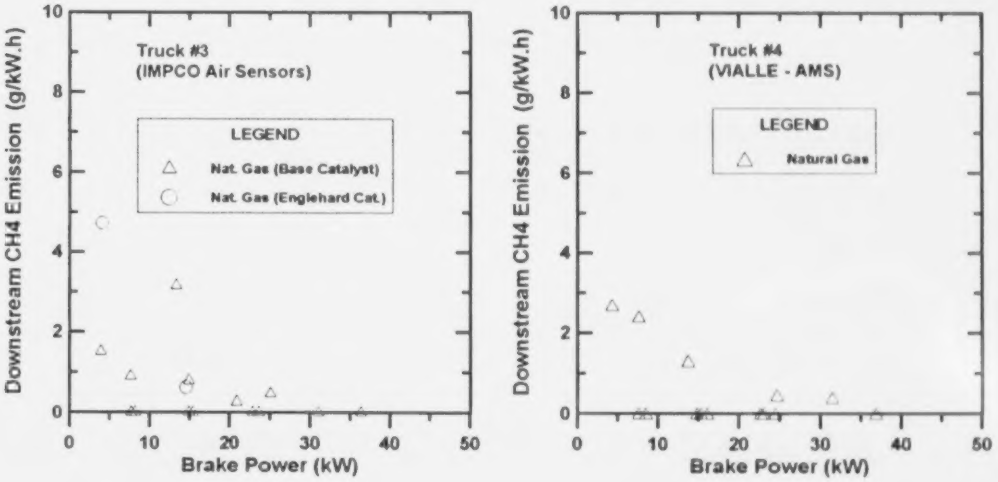

Figure 5.24c: Truck #3 (IMPCO)

Figure 5.24d: Truck #4 (VIALLE)

Figure 5.24: Tailpipe Methane Hydrocarbons (CH_4) Emission Results with Gasoline and Natural Gas Fuelling for the Various Trucks (Conversion Systems) at Part-Load (Multi-Modes)

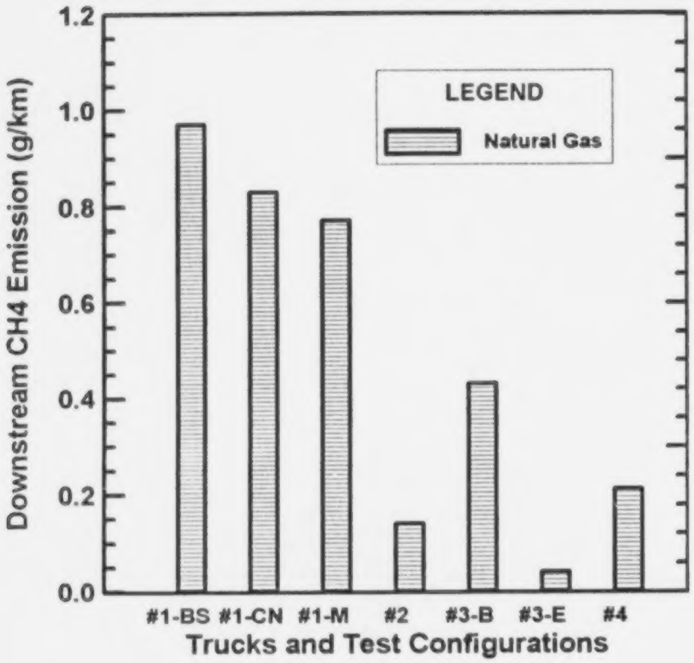

Figure 5.25: Comparison of the Composite Tailpipe Methane Hydrocarbons (CH_4) Emission Results at Part-Load (Multi-Mode Tests)
Where:
#1-BS is Truck #1 (ANGI) "Baseline" (Gas.) and "Spark Advanced" (NG)
#1-CN is Truck #1 (ANGI) "Converted" (Gas.) and "No Spark Advanced" (NG)
#1-M is Truck #1 (ANGI) "Mixer Adjusted" (NG)
#2 is Truck #2 (GFI)
#3-B is Truck #3 (IMPCO) "Base Catalyst"
#3-E is Truck #3 (IMPCO) "Englehard Catalyst"
#4 is Truck #4 (VIALLE)

5.2 WIDE-OPEN THROTTLE TESTS (WOT) RESULTS

Each of the trucks was run at wide-open-throttle on both gasoline and natural gas to generate torque and power curves and, hence, determine the peak torque and peak power for each test configuration. As well as measuring the average equivalence ratio, the brake thermal efficiency for each truck on each fuel was determined. All the brake power and torque results were corrected to standard atmospheric conditions according to SAE Standard J1349. The power correction factors ranged between 2 % and 4 % and were thus, within the acceptable value of 5 %.

5.2.1 Brake Power

Figures 5.26a, 5.26b, 5.26c, and 5.26d show the corrected brake power against engine speed curves for the trucks at wide-open throttle (WOT), while figure 5.27 shows a comparison of the peak power values.

For all the trucks, on both gasoline and natural gas operations, the curves follow the classical relationship of power increasing with speed at low speeds until a maximum point before top speed. The brake power is the product of the net indicated power and the mechanical efficiency. Assuming constant intake pressure, the intake power increases directly with engine speed. However, the intake flow loss increases with the square of engine speed, thereby limiting the peak indicated power to less than the maximum speed. Friction power also increases with the square of the engine speed as does the power required by the cooling fan. Hence the mechanical efficiency decreases at high speed causing the brake power to exhibit a maximum within the normal operating speed range.

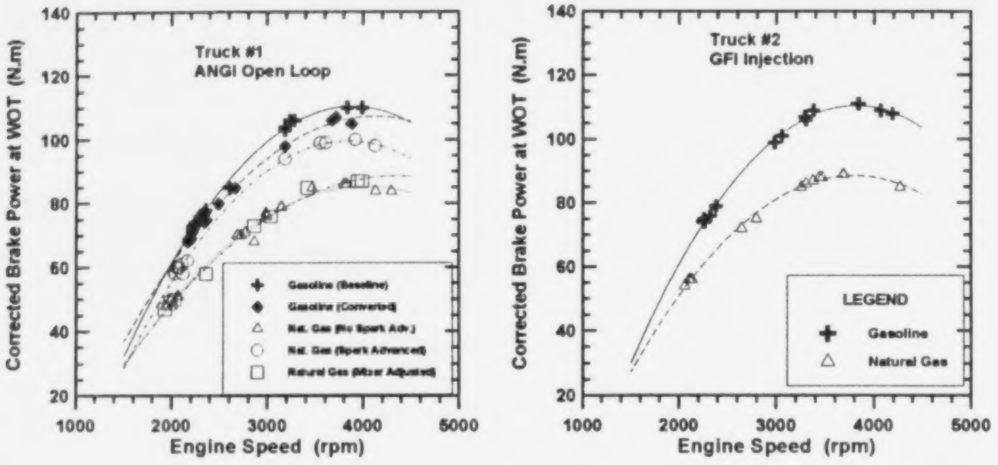

Figure 5.26a: Truck #1 (ANGI Open-Loop)

Figure 5.26b: Truck #2 (GFI)

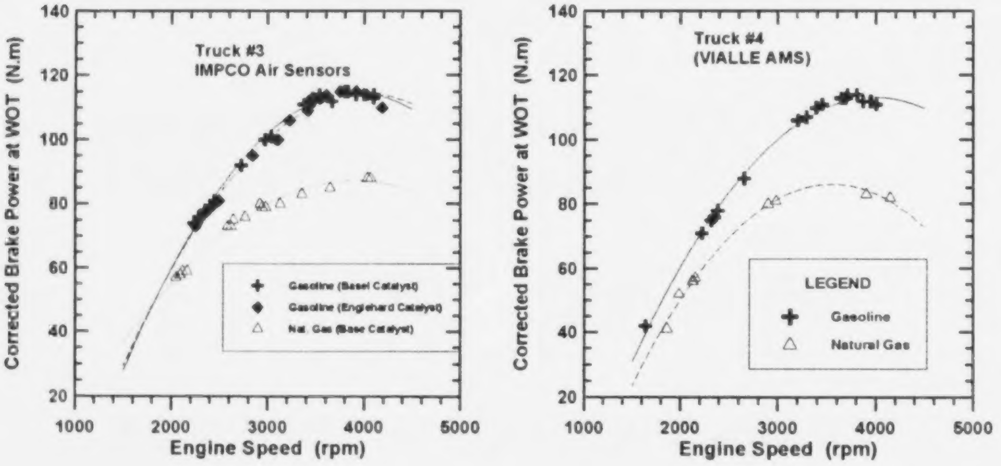

Figure 5.26c: Truck #3 (IMPCO)

Figure 5.26d: Truck #4 (VIALLE)

Figure 5.26: Corrected Brake Power Results with Gasoline and Natural Gas Fuelling for the Various Trucks (Conversion Systems) at Wide-Open Throttle

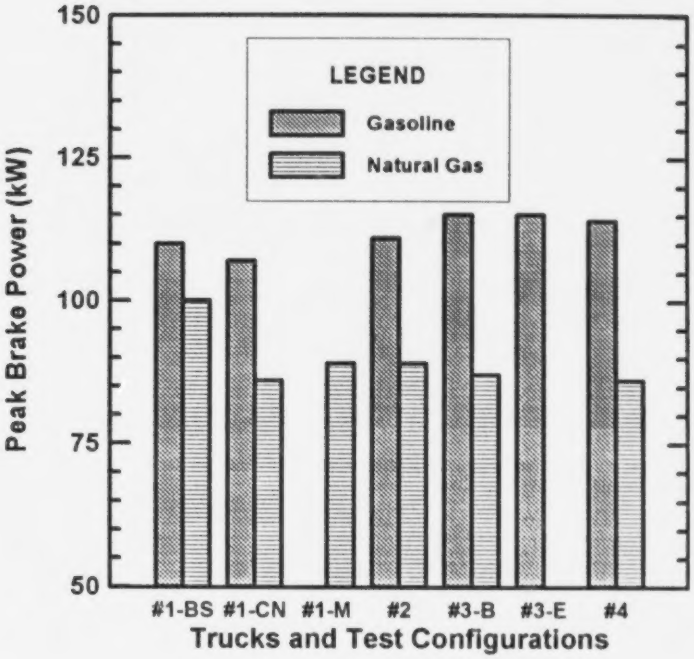

Figure 5.27: Comparison of the Peak Brake Power Values at Wide-Open Throttle (WOT)

Where:

#1-BS is Truck #1 (ANGI) "Baseline" (Gas.) and "Spark Advanced" (NG)
#1-CN is Truck #1 (ANGI) "Converted" (Gas.) and "No Spark Advanced" (NG)
#1-M is Truck #1 (ANGI) "Mixer Adjusted" (NG)
#2 is Truck #2 (GFI)
#3-B is Truck #3 (IMPCO) "Base Catalyst"
#3-E is Truck #3 (IMPCO) "Englehard Catalyst"
#4 is Truck #4 (VIALLE)

The speed at which the maximum power values were obtained varied from 3850 rpm to 4000 rpm for gasoline operation, and from 3600 rpm to 4300 rpm for natural gas operation.

Most conversions had little or no effect on the maximum power during gasoline operation, while there was greater variability in the gaseous fuel operation. On gasoline, the peak power ranged between 110 and 115 kW with a mean value of 112 kW. On natural gas, the peak power values for the other trucks with feedback control (#2, #3 and #4), were very similar, 89 kW, 87 kW and 89 kW, respectively, with a mean value of 87 kW. This shows that all the conversions worked about equally well. For the ANGI open-loop conversion, with the spark advanced, the maximum power was about 100 kW (the highest on natural gas operation). This high value is due to the extra advance spark, required to compensate for the slow burning speed of natural gas. Without the spark advance, the peak power dropped to about 86 kW, while the adjustment of the mixer for richer air-fuel ratio operation increased the peak power to about 89 kW. At 2000 rpm (closer to normal vehicle operating speed than the peak power speeds), the brake power on gasoline was approximately equal to 60 kW for each of the trucks, while on natural gas the power ranged between 50 and 53 kW with a mean value of 51.3 kW.

Each of the trucks experienced a reduction in power while operating on natural gas compared to gasoline. The loss in power on natural gas was more evident at higher power values. The loss of maximum power ranged from about 9.6% for the ANGI open-loop (with the spark advanced) to about 24.2 % for the VIALLE-AMS with an average of 19.2 %. At 2000 rpm, the power loss ranged between 6.67 % and 16.7 % with a mean value of 13.8 %. This power loss is caused by the absence of evaporative charge cooling on natural gas, loss of volumetric efficiency (about 10 %), slower burning speed of natural gas, and to a lesser extent, the presence of some carbon dioxide in the fuel. The loss could also be due to the greater fuel enrichment on gasoline. Gasoline engines converted to run on natural gas without optimization for the gaseous fuel are always expected to lose about 10 % or more power [10, 13]. Tests carried out by Segal and Keffer [17], Evans et al. [12], Bell et al. [11] and Varde [9] showed power losses of 12.3 to 22.1 %, 11.3 to 16.6 %, 13 to 16 %, and 9 to 14 %, respectively. The differences in the power losses obtained on natural gas by the various investigators were probably due to the differing operating speeds and other test conditions.

On natural gas, the mean equivalence ratio was about 1.0 with a range of 0.89 to 1.10, while on gasoline, the ratio varied between 1.09 and 1.38 with a mean value of 1.24 and a standard deviation of 0.10. However, this large fuel enrichment on gasoline led to a reduction in the brake thermal efficiency at peak torque. On gasoline, the mean thermal efficiency was 21.9 %, while it was equal to 22.8 % on natural gas. (The lower heating value of gasoline was taken to be 43.5 while that for natural gas was found to be equal to 45.9 MJ/kg. This value was obtained from the heating values of the constituent gases and their percentage compositions [28]).

5.2.2 Brake Torque

Figure 5.25a, 5.28b, 5.28c and 5.28d show the plots of corrected torque against engine speed. Each truck lost some torque while operating on natural gas, with the maximum loss occurring around the peak torque for the closed-loop conversions. On gasoline, peak torque ranged between 305 (2500 rpm) and 322 N.m (2850 rpm) with a mean value of 318 N.m, while the mean value on natural gas, for the trucks with closed-loop conversions, was 263 N.m with a range of 260 N.m (2650 rpm) to 268 N.m (2280 rpm). The average loss of peak torque on natural gas was about 17.3 %. Again the highest peak torque of 287 N.m was obtained from truck #1 (ANGI with the spark advanced), while the lowest value of 242 N.m. was obtained after the mixer was adjusted (for truck #1) to obtain richer air-fuel mixtures. Figure 5.29 shows the peak torque values.

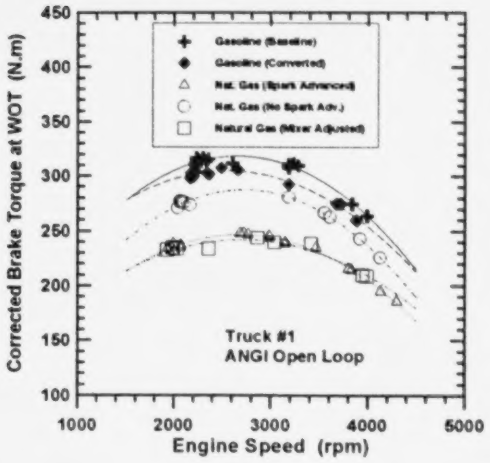

Figure 5.28a: Truck #1 (ANGI Open-Loop)

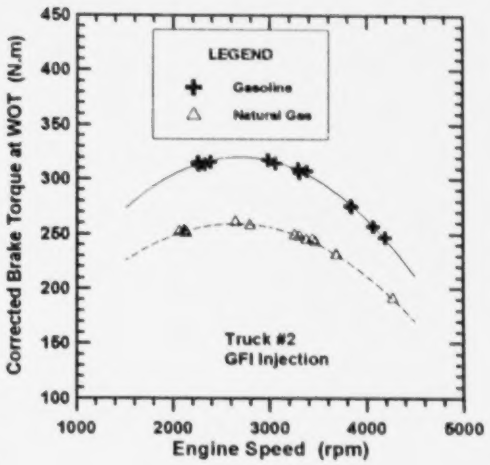

Figure 5.28b: Truck #2 (GFI)

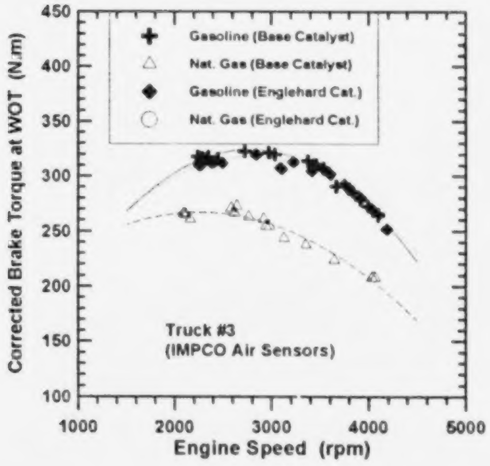

Figure 5.28c: Truck #3 (IMPCO)

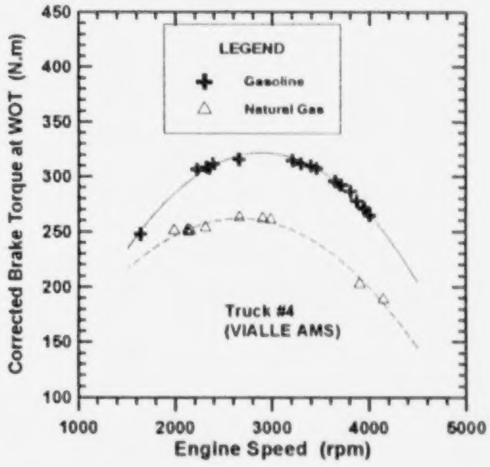

Figure 5.28d: Truck #4 (VIALLE)

Figure 5.28: Corrected Brake Torque Results with Gasoline and Natural Gas Fuelling for the Various Trucks (Conversion Systems) at Wide-Open Throttle

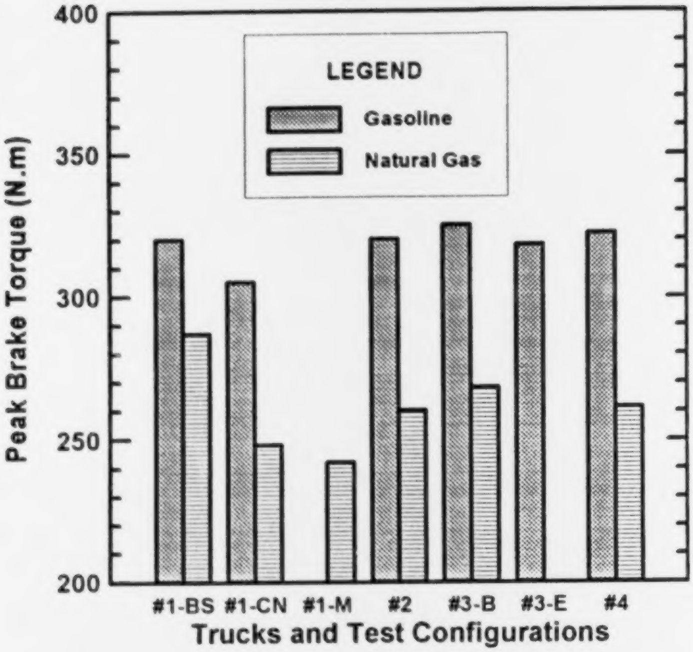

Figure 5.29: Comparison of the Peak Brake Torque Values at Wide-Open Throttle (WOT)
Where:
#1-BS is Truck #1 (ANGI) "Baseline" (Gas.) and "Spark Advanced" (NG)
#1-CN is Truck #1 (ANGI) "Converted" (Gas.) and "No Spark Advanced" (NG)
#1-M is Truck #1 (ANGI) "Mixer Adjusted" (NG)
#2 is Truck #2 (GFI)
#3-B is Truck #3 (IMPCO) "Base Catalyst"
#3-E is Truck #3 (IMPCO) "Englehard Catalyst"
#4 is Truck #4 (VIALLE)

5.3 COMPARISON OF THE PERFORMANCE OF THE CONVERSION SYSTEM

As noted earlier, four different natural gas conversion systems were used for the study. The systems were:

1. The Angi- Low Emission Vehicle (LEV) System
2. The Stewart and Stevenson/Ortech - Gaseous Fuel Injection (GFI)
3. Impco/Air Sensors - Alternative Fuel Electronic (AFE) System
4. Vialle - Autogas Management System (AMS)

Tables 5.1 to 5.5 show the ranking of the performance and emission characteristics of the various conversion systems for both the multi-mode and wide-open throttle tests. The results for the gaseous fuel injection (GFI) kit are used as a standard for rating the performance of the other three conversion kits. The fuel consumption and mixture control results are given on table 5.1, while the engine-out and tailpipe emissions results are compared in table 5.2 and 5.3 respectively. Table 5.4 compares the catalyst conversion efficiencies, while table 5.5 gives the peak power and peak torque results at wide-open throttle.

5.3.1 ANGI - Low Emission Vehicle (LEV) System (Open-Loop)

The Angi open-loop conversion, as expected, without spark advance, gave the worst air-fuel mixture control as the truck gave the leanest operation of all the natural gas test configurations, as shown in table 5.1. The range of the equivalence ratio for this test configuration was also the widest. The fuel consumption and the engine-out carbon dioxide emissions were thus found to be one of the best of all the conversions, as shown in table 5.2.

The conversion gave the best tailpipe CO and RHC emissions of all conversions, while the corresponding NOx and CH_4 emissions were average and worst, respectively. These are shown in table 5.3. The low tailpipe CO and RHC emissions resulted from the lean operation which led to the low engine-out emissions and high catalyst conversion efficiencies of the two exhaust components, shown in table 5.4. The peak power and peak torque were slightly lower than those of the closed-loop conversions. These are shown in table 5.5.

By adjusting the mixer, the mean air-fuel ratio increased to near stoichiometric, while the tailpipe CO and CH_4 emissions were accordingly increased. The fuel enrichment also led to a slight increase in the peak power. With spark advance, the ANGI conversion, as expected, gave the best fuel consumption, the lowest CO_2 emissions, and the highest NOx emissions. The highest peak power and peak torque values, on natural gas were also obtained from this configuration.

5.3.2 Stewart and Stevenson / Ortech - Gaseous Fuel Injection (GFI)

The mixture control of the Gaseous Fuel Injection (GFI) conversion system was less "ideal" than the other closed-loop systems as the truck ran lean on some modes. Hence, the conversion had the best fuel economy and the lowest CO_2 emissions. The conversion produced the lowest tailpipe CO, RHC and CH_4 emissions and the highest NOx emission, as shown in table 5.3. Due to the lean operation, the CO, RHC and CH_4 catalyst conversion efficiencies were the best of all the closed-loop systems, while the

NOx conversion efficiency was the worst. The peak power and peak torque were comparable to those of the IMPCO and VIALLE (closed-loop systems).

5.3.3 IMPCO/Air Sensors Alternative Fuel Electronic (AFE) System

As expected, there were little differences between the results obtained for the two IMPCO tests configurations: using base catalyst and using Englehard (new) catalyst. With the base catalyst, truck #3 (the IMPCO conversion), ran closer to stoichiometric operation than when the Englehard catalyst was installed. The engine-out emissions were about the average values for the closed-loop conversion. The tailpipe NOx emissions were the lowest of the closed-loop conversions while the CO and CH_4 were the highest. The catalyst conversion efficiencies were found to be comparable to those of the GFI conversion. The peak power and peak torque at wide-open-throttle were similar to those of the other closed-loop systems.

With the installation of a brand new (Englehard) catalyst, the tailpipe NOx, CH_4 were decreased, while the RHC and CO emissions were increased. This was mainly due to the increase of NOx and CH_4 conversion efficiencies and the reduction of CO and RHC efficiencies of the new catalyst.

5.3.4 VIALLE - Autogas Management System (AMS)

This system had the best air-fuel mixture control as the average air-fuel ratio was almost equal to stoichiometric (highest of all the conversions). Due to the richer operation, the fuel consumption and CO_2 emissions were the highest of all conversions.

The richer operation also led to reduced (lower than average) CO, RHC and CH_4 conversion efficiency. The tailpipe NOx and RHC emissions were the highest of all the closed-loop conversions while the CO and CH_4 emissions were about average.

Table 5.1: Comparison of the Fuel Consumption and Mixture Control Performance of the Four different Conversion Kits

	ANGI Spark Advance (%)	ANGI No Spark (%)	ANGI Mixer Adjusted (%).	GFI (%)	IMPCO Base Catalyst (%)	IMPCO Engle. Catalyst (%)	VIALLE (%)
Mixture Control	89.1	93.6	103.3	100	104.5	98.9	106.5
Fuel Consumption	92.9	99.2	98.4	100	103.1	103.1	104.7

Table 5.2: Comparison of the Engine-out Emissions Performance of the four Different Conversion Kits

	ANGI Spark Advance (%)	ANGI No Spark (%)	ANGI Mixer Adjusted (%)	GFI (%)	IMPCO Base Catalyst (%)	IMPCO Engle. Catalyst (%)	VIALLE (%)
CO_2	95.3	102.5	103.2	100	100.9	102.8	110.7
NOx	153.8	73.6	n/a	100	111.3	80.2	103.8
CO	19.3	21.3	n/a	100	77.3	88.4	31.5
RHC	80.0	46.7	n/a	100	173.3	173.3	240.0
CH_4	111.1	93.9	n/a	100	129.3	133.3	39.4

Table 5.3: Comparison of the Tailpipe Emissions Performance of the Four Different Conversion Kits

	ANGI Spark Advance (%)	ANGI No Spark (%)	ANGI Mixer Adjusted (%)	GFI (%)	IMPCO Base Catalyst (%)	IMPCO Engle. Catalyst (%)	VIALLE (%)
NOx	157.6	103.0	109.1	100	60.6	30.3	125.8
CO	114.3	47.6	190.4	100	285.7	538.1	233.3
RHC	14.3	0	0	100	200	228.6	371.4
CH_4	692.9	592.9	550	100	307	285.7	150.0

Table 5.4: Comparison of the Catalyst Conversion Efficiency Performance of the Four Different Conversion Kits

	ANGI Spark Advance (%)	ANGI No Spark (%)	ANGI Mixer Adjusted (%)	GFI (%)	IMPCO Base Catalyst (%)	IMPCO Engle. Catalyst (%)	VIALLE (%)
NOx	96	34.0	n/a	100	175.3	202.9	65.3
CO	90	97.7	n/a	100	95.0	90.9	88.1
RHC	172.1	187.6	n/a	100	86.7	72.23	52.2
CH_4	13.7	12.6	n/a	100	77.3	113.4	53.8

Table 5.5: Comparison of the Wide-Open Throttle Test Performance of the Four Conversion Kits

	ANGI Spark Advance (%)	ANGI No Spark (%)	ANGI Mixer Adjusted (%)	GFI (%)	IMPCO Base Catalyst (%)	IMPCO Engle. Catalyst (%)	VIALLE (%)
Peak Power	112.3	96.6	100.0	100	97.8	n/a	96.6
Peak Torque	110.4	95.4	93.1	100	103.1	n/a	100.4
Thermal Efficiency	94.7	102.3	121.3	100	103.1	n/a	117.0

CHAPTER 6

SUMMARY AND CONCLUSION

6.1 SUMMARY

The objective of the present study was to evaluate the performance characteristics of four converted GMC 2500 series 3/4 ton trucks running on gasoline and natural gas. Each vehicle had a different conversion system. Three of the trucks had natural gas conversion kits with closed loop feed-back control (GFI, Impco and Vialle), while one (Angi) had an open-loop system. The open-loop systems are typical of most current conversions.

Each vehicle was tested on a drive-shaft dynamometer on a steady-state multi-mode schedule and at wide-open-throttle (WOT). The multi-mode test schedule (part-load) is based on a tractive energy analysis of the Federal Testing Procedure of 1978 (FTP-78) certification tests and it exercised each of the vehicles over the same range of speeds and loads as the Federal Testing Procedure, FTP-78. The test schedule involved running the vehicle at fifteen speed/load points chosen to represent typical light duty operating conditions. For this part-load operation, the fuel consumption, equivalence ratio, engine-out and tailpipe emissions, and the catalytic converter effectiveness were evaluated. The WOT tests involved running each of the trucks at maximum throttle over a range of engine speeds to obtain the maximum power/speed and maximum torque/speed curves. The effects of speed on the brake power and brake torque, as well as the peak power and torque values were obtained for each fuel configuration.

There was no clear trend of air-fuel equivalence ratio with power for the multi-mode tests. The best control was obtained on gasoline and the three trucks with closed-loop conversion kits (on natural gas) maintained tighter control on the air-fuel ratio than the open loop conversion. On average, the trucks ran leaner and also had a greater thermal efficiency on natural gas than on gasoline.

For part-load operation (multi-mode tests), there was little variability between the composite fuel consumption on gasoline, showing that the added conversion equipment had very little effect on the trucks' gasoline consumption. The best fuel economy on natural gas (14.5 % reduction from gasoline) was obtained from truck #1 (with the ANGI open-loop conversion) when the spark was advanced to compensate for the slower burning speed of natural gas. On average, the trucks with closed-loop conversion had a 5 % average reduction in fuel consumption on natural gas. This reduction is due mainly to the higher calorific value, and the leaner operation on natural gas.

The brake specific engine-out carbon dioxide (CO_2) emission followed the fuel consumption as expected. There was little difference between conversions for either gasoline or natural gas operation, though the advancement of the spark for the open-loop conversion resulted in the lowest CO_2 emissions on gaseous fuel. CO_2 emissions were reduced by about 20 % on natural gas because of the lower fuel consumption and the lower carbon content per unit fuel mass.

The engine-out emissions of oxides of nitrogen (NOx), carbon monoxide (CO), and reactive non-methane hydrocarbons (RHC), were generally lower on natural gas. For the trucks with closed-loop conversion, the mean engine-out NOx emissions were down by 35.6 %; the CO by 10.3 % and the RHC by 81.3 %. The methane (CH_4) emissions on gasoline were negligible, while on natural gas, they comprised only about 0.08 % of the vehicle fuel. Methane is not considered to be a significant pollutant since it does not contribute to smog or acid formation and is produced in very low levels compared with green house gases like carbon dioxide (CO_2).

The catalyst conversion rates of the various raw exhaust gas components were found to increase with power, with the amount of reducing agents in the raw exhaust (for NOx conversion), and with the amount of oxidizing agents (for CO, THC and RHC conversions). The catalytic converters were found to be less effective on natural gas than on gasoline. This was probably due to the less precise mixture control on natural gas. For the trucks with closed-loop conversion systems, the average NOx, CO, and RHC conversion efficiencies were reduced by 34.4 %, 3.8 %, and 52.7 %, respectively, on natural gas. For the open-loop conversion system, the NOx and CO efficiencies were reduced by 68.6 % and 2.9 %, respectively, while the RHC efficiency increased by 9.4 %.

On average, the tailpipe NOx, CO and RHC emissions were up by 73.3 %, 13.0 %, and 6.67 %, respectively, on natural gas. Though there was greater truck-by-truck variability on natural gas, the emission levels were generally low. The tailpipe emissions from these new trucks on both gasoline and natural gas were generally lower than those produced by the average vehicle on the street.

There was very little variation in the peak power and peak torque produced by the trucks on gasoline. The peak power values varied between 107 and 115 kW, while the peak torque ranged between 305 and 325 N.m. Each truck lost a substantial amount of peak power while on natural gas, and the average loss for the trucks was 19.2 %.

However, an examination of the power and torque curves showed that the loss was less significant at low speeds (below 2500 rpm) which are important for truck operation. At 2000 rpm, the mean power loss was 13.8 %

The ANGI open-loop conversion with the spark advanced, produced the highest peak power and peak torque on natural gas (110 kW and 287 N.m), while the other trucks, each fitted with a closed-loop natural gas conversion system, had almost identical results (range of 86 kW to 89 kW for power and 260 to 268 N.m for peak torque).

The emissions, fuel economy and power results obtained from the truck with the ANGI open-loop conversion, were different from those obtained from the trucks with closed-loop conversions. This ANGI conversion had less precise mixture control such that the converted truck ran lean on natural gas. The lean operation led to low engine-out CO, RHC and CH_4 emissions (compared to the closed-loop conversions). However, the poor mixture control resulted in low catalyst conversion effectiveness. Using a spark advance box to compensate for the lower burning speed of natural gas increased the peak power and peak torque at WOT, and improved the fuel economy, and hence, reduced CO_2 emissions. However, there was a significant increase in NOx emissions associated with the extra spark advance.

The truck using the GFI-injection system ran leaner than the other closed-loop converted trucks and therefore had the best fuel economy and the lowest CO_2 emissions. It also produced the lowest CO, RHC, CH_4, and the highest NOx emissions. The IMPCO conversion produced the lowest tailpipe NOx emissions, the highest CO and the highest CH_4 of all the closed-loop conversion systems. The truck using the VIALLE conversion system operated very close to stoichiometric (richest of all closed-loop conversions) and thus had the highest fuel consumption and CO_2 emissions. It also produced the highest tailpipe NOx and RHC emissions.

However, the emissions levels of the trucks were generally very low and so the variations cannot be considered to be very significant. The variation in the results could be due to the calibrations made on the systems or due to the variation in the testing conditions.

6.2 CONCLUSION

The results from the study show that natural gas can be used as an alternative spark-ignition engine fuel to supplement the non-renewable gasoline fuel. Given the better fuel economy on natural gas and the lower unit cost, and refining and transportation costs, cost savings may be obtained with natural gas-fuelled vehicles compared to gasoline vehicles. Natural gas has been promoted as a cleaner burning engine fuel, producing lower exhaust emissions than gasoline. Though the trucks produced lower engine-out emissions on natural gas than on gasoline, the tailpipe emissions of NOx and CO were slightly higher on natural gas because of poorer fuel control which reduced the catalyst conversion efficiencies for regulated exhaust emissions. In any case, the emission levels were generally lower than those produced by the average vehicle on the street. One of the main arguments against natural gas as spark ignition fuel, is the loss of power on the gaseous fuel. Though all conversions lost power and torque on natural gas, the loss was less significant at the lower engine speeds at which the trucks are normally operated.

Although differences exist in the performance of the four tested conversion kits, each of them performed very well, especially those with closed-loop feed-back control. However, the fuel control systems of each of the conversion kits still need to be improved to make them as effective as the state-of-the-art gasoline engines. Such improvement would lead to better vehicle performance and better catalytic converter effectiveness on natural gas.

It is hoped that more vehicles will be converted to run on natural gas so as to creat the fuel demand that will justify the development of the entire natural gas fuelling infrastructure. This might lead to the eventual replacement of conversion vehicles with dedicated technology and the use of natural gas as a vehicle fuel on a larger scale.

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APPENDIX A

Multi-Mode Composite Results and WOT Results

This Appendix gives the multi-mode composite emissions and fuel consumption results for both gasoline and natural gas operations. The Appendix also gives the peak power and peak torque results at wide-open throttle.

Table A.1a: Composite CO_2, O_2, and Fuel Consumption Results of Multi-mode Tests on Gasoline

TRUCK	Fuel Consumption (kg/100 km)	Engine-out O_2 (g/km)	Tailpipe O_2 (g/km)	CO_2 Emissions (g/km)
Truck #1 (ANGI - Open Loop)				
Baseline	13.5		0.14	400
Converted	14.1	12.5	0.35	413
Truck #2 (GFI Injection)	13.6	14.4	0.56	414
Truck #3 (IMPCO Air Sensors)	13.9	14.1	2.42	412
Base Catalyst	13.7	13.6	4.06	404
Englehard Catalyst				
Truck #4 (VIALLE - AMS)	13.9	12.3	1.95	414
MEAN (#1 included)	**13.8**	**13.3**	**1.58**	**410**
STANDARD DEVIATION (#1 included)	**0.22**	**0.94**	**1.52**	**5.99**

Table A.1b: Composite CO_2, O_2, and Fuel Consumption Results of Multi-mode Tests on Natural Gas

TRUCKS	Fuel Consumption (kg/100 km)	Engine-out O_2 (g/km)	Tailpipe O_2 (g/km)	CO_2 Emissions (g/km)
Truck #1 (ANGI Open Loop)				
Spark Advance	11.8	54.8	47.8	302
No Spark Advance	12.6	49.4	41.8	325
Mixer Adjusted	12.5		29.0	327
Truck #2 (GFI Injection)	12.7	42.4	17.3	317
Truck #3 (IMPCO - Air Sensors)	13.1	33.5	17.1	320
Base Catalyst	13.1	38.3	10.3	326
Englehard Catalyst				
Truck #4 (VIALLE AMS)	13.3	19.2	16.3	351
MEAN (#1 included)	**12.7**	**39.6**	**25.7**	**324**
STANDARD DEVIATION (#1 included)	**0.52**	**12.5**	**14.3**	**14.7**
MEAN (#1 not included)	**13.1**	**33.4**	**15.3**	**329**
STANDARD DEVIATION (#1 not included)	**0.25**	**10.1**	**3.4**	**15.5**

Table A.2a: Composite Engine-out Emission Results of Multi-mode Tests on Gasoline

TRUCK	NOx (g/ km)	CO (g/km)	RHC (g/km)	CH_4 (g/km)
Truck #1 (ANGI Open Loop)				
Baseline	n/a	n/a	n/a	n/a
Converted	2.05	11.3	1.54	0
#2 (GFI Injection)	1.46	11.4	1.00	0.01
Truck #3 (IMPCO Air Sensors)				
Base Catalyst	1.70	8.30	1.33	0.01
Englehard Catalyst	1.34	7.98	1.71	0.0
Truck #4 (VIALLE AMS)	1.62	8.76	1.39	0.0
MEAN (#1 included)	**1.63**	**9.56**	**1.39**	**0.0**
STANDARD DEVIATION (#1 included)	**0.27**	**1.68**	**0.26**	**0.0**

Table A.2b: Composite Engine-out Emission Results of Multi-mode Tests on Natural Gas

TRUCKS	NOx (g/km)	CO (g/km)	RHC (g/km)	CH_4 (g/km)
Truck #1 (ANGI Open Loop)				
Spark Advance	1.63	2.23	0.12	1.10
No Spark advance	0.78	2.45	0.07	0.93
Mixer Adjusted	n/a	n/a	n/a	n/a
Truck #2 (GFI Injection)	1.06	11.54	0.15	0.99
Truck #3 (IMPCO Air Sensors)				
Base Catalyst	1.18	8.92	0.26	1.28
Englehard Catalyst	0.85	10.2	0.26	1.32
Truck #4 (VIALLE AMS)	1.10	3.64	0.36	0.39
MEAN (#1 included)	**1.05**	**6.50**	**0.20**	**1.00**
STANDARD DEVIATION (#1 included)	**0.15**	**4.19**	**0.11**	**0.34**
MEAN (#1 not included)	**1.05**	**8.58**	**0.26**	**1.00**
STANDARD DEVIATION (#1 not included)	**0.14**	**3.46**	**0.11**	**0.43**

Table A.3a: Composite Tailpipe Emission Results of Multi-mode Tests on Gasoline

TRUCK	NOx (g/ km)	CO (g/km)	RHC (g/km)	CH4 (g/km)
Truck #1 **(ANGI Open Loop)**				
Baseline	0.04	0.90	0.10	0.00
Converted	0.25	0.70	0.20	0.00
#2 **(GFI Injection)**	0.23	0.78	0.20	0.01
Truck #3 **IMPCO Air Sensors**				
Base Catalyst	0.60	0.32	0.14	0.00
Englehard Catalyst	0.43	0.21	0.09	0.00
Truck #4 **VIALLE AMS**	0.23	0.33	0.18	0
MEAN (#1 included)	**0.30**	**0.54**	**0.15**	**0.00**
STANDARD DEVIATION (#1 included)	**0.19**	**0.29**	**0.05**	**0.00**

Table A.3b: Composite Tailpipe Emission Results of Multi-mode Tests on Natural Gas

TRUCKS	**NOx (g/km)**	**CO (g/km)**	**RHC (g/km)**	**CH4 (g/km)**
Truck #1 (ANGI Open Loop)				
Spark Advance	1.04	0.24	0.01	0.97
No Spark Advance	0.68	0.10	0.00	0.83
Mixer Adjusted	0.72	0.40	0.00	0.77
Truck #2 (GFI Injection)	0.66	0.21	0.07	0.14
Truck #3 (IMPCO Air Sensors)				
Base Catalyst	0.40	0.60	0.14	0.43
Englehard Catalyst	0.20	1.13	0.16	0.04
Truck #4 (VIALLE AMS)	0.83	0.49	0.26	0.21
MEAN (#1 included)	**0.65**	**0.45**	**0.09**	**0.48**
STANDARD DEVIATION (#1 included)	**0.28**	**0.34**	**0.10**	**0.37**
MEAN (#1 not included)	**0.52**	**0.61**	**0.16**	**0.21**
STANDARD DEVIATION (#1 not included)	**0.28**	**0.39**	**0.08**	**0.17**

Table A.4a: Composite Catalyst Conversion Efficiency Results of Multi-mode Tests on Gasoline

TRUCK	NOx (%)	CO (%)	RHC (%)	CH4 (%)
Truck #1 (ANGI Open Loop)				
Baseline	n/a	n/a	n/a	
Converted	87.8	93.8	87.0	-
Truck #2 (GFI Injection)	84.3	93.2	80.0	-
Truck #3 (IMPCO Air Sensors)				
Base Catalyst	64.7	96.1	89.5	-
Eng. Catalyst	67.9	97.4	94.7	-
Truck #4 (VIALLE - AMS)	85.8	96.2	87.1	-
MEAN (#1 included)	**78.1**	**95.4**	**87.7**	-
STANDARD DEVIATION (#1 included)	**10.9**	**1.77**	**5.31**	-

Table A.4b: Composite Catalyst Conversion Efficiency Results of Multi-mode Tests D Natural Gas

TRUCKS	NOx (%)	CO (%)	RHC (%)	CH4 (%)
Truck #1 (ANGI Open Loop) **Spark Advance** **No Spark Advance** **Mixer Adjusted**	 36.2 12.8 n/a	 89.2 95.9 n/a	 91.7 100 n/a	 11.8 10.8 n/a
Truck #2 (GFI Injection)	37.7	98.2	53.3	85.9
Truck #3 (IMPCO Air Sensors) **Base Catalyst** **Englehard Catalyst**	 66.1 76.5	 93.3 89.0	 46.2 38.5	 66.4 97.0
Truck #4 (VIALLE AMS)	24.6	86.5	27.8	46.2
MEAN (#1 included)	**43.3**	**92.0**	**59.6**	**53.0**
STANDARD DEVIATION (#1 included)	**24.4**	**4.51**	**29.5**	**36.7**
MEAN (#1 not included)	**51.2**	**91.8**	**41.5**	**73.9**
STANDARD DEVIATION (#1 not included)	**24.2**	**5.14**	**10.9**	**22.4**

Table A.5a: Wide-Open Throttle (WOT) Brake Power Results On Gasoline

TRUCK	**Peak Power (kW)**	**Speed at Peak Power (rpm)**	**Power at 2000 rpm (kW)**
Truck #1 (ANGI)			
Baseline	110	3900	60
Converted	107	4150	60
Truck #2 (GFI)	111	3850	60
Truck #3 (IMPCO)			
B/Catalyst	115	3900	60
E/Catalyst	115	4000	60
Truck #4 (VIALLE)	114	4000	60
MEAN (#1 incl.)	**112**	**3970**	**60**
STANDARD DEVIATION (#1 included)	**3.22**	**108**	**0**

Table A.5b: Wide-Open Throttle (WOT) Power Results on Natural Gas

TRUCK	Peak Power (kW)	Speed at Peak Power (rpm)	Power at 2000 (rpm) (kW)
Truck #1 (ANGI)			
Spark Advanced	100	3850	56
No Spark Advance	86	4000	50
Mixer Adj.	89	4300	50
Truck #2 (GFI)	89	3800	51
Truck #3 (IMPCO)			
Base Catalyst	87	3950	53
Engle. Catalyst	n/a	n/a	n/a
Truck #4 (VIALLE)	86	3600	50
MEAN (#1 incl.)	**89.5**	**3920**	**51.7**
STANDARD DEVIATION (#1 incl.)	**5.32**	**234**	**2.4**
MEAN (#1 not included)	**87.3**	**3780**	**51.3**
STANDARD DEVIATION (#1 not included)	**1.52**	**176**	**1.53**

Table A.6a: Wide-Open Throttle (WOT) Brake Torque Results On Gasoline

TRUCK	**Peak Torque (N.m)**	**Speed at Peak Torque (rpm)**	**Torque at 2000 rpm (N.m)**
Truck #1 (ANGI)			
Baseline	302	2650	305
Converted	305	2500	298
Truck #2 (GFI)	320	2700	305
Truck #3 (IMPCO)			
Base Catalyst	325	2800	303
Engle. Catalyst	318	2800	300
Truck #4 (VIALLE)	322	2850	285
MEAN (#1 incl.)	**318**	**2717**	**299**
STANDARD DEVIATION (#1 included)	**6.94**	**129**	**7.55**

Table A.6b: Wide-Open Throttle (WOT) Brake Torque Results on Natural Gas

TRUCK	Peak Power (N.m)	Speed at Peak Power (rpm)	Power at 2000 (N.m)
Truck #1 (ANGI)			
Spark Advanced	287	2750	270
No Spark Advance	248	2750	236
Mixer Adj.	242	2700	232
Truck #2 (GFI)	260	2650	249
Truck #3 (IMPCO)			
Base Catalyst	268	2280	255
Engle. Catalyst	n/a	n/a	n/a
Truck #4 (VIALLE)	261	2700	248
MEAN (#1 incl.)	**261**	**2650**	**248**
STANDARD DEVIATION (#1 incl.)	**15.8**	**179**	**13.7**
MEAN (#1 not included)	**263**	**2570**	**251**
STANDARD DEVIATION (#1 not included)	**4.36**	**195**	**3.79**

Table A.7a: Wide-Open Throttle (WOT) Mean Thermal Efficiency and Equivalence Ratio Results on Gasoline

TRUCK	Thermal Efficiency (%)	Equivalence Ratio
Truck #1 (ANGI)		
Baseline	24.8	1.09
Converted	21.4	1.17
Truck #2 (GFI)	20.7	1.28
Truck #3 (IMPCO)		
B/Catalyst	21.8	1.26
E/Catalyst	21.6	1.25
Truck #4 (VIALLE)	21.0	1.38
MEAN (#1 incl.)	**21.9**	**1.24**
STANDARD DEVIATION (#1 included)	**1.48**	**0.10**

Table A.7b: Wide-Open Throttle (WOT) Mean Thermal Efficiency and Equivalence Ratio Results on Natural gas

TRUCK	Thermal Efficiency (%)	Equivalence Ratio
Truck #1 (ANGI)		
Spark Advanced	27.5	0.89
No Spark Advance	22.7	0.96
Mixer Adj.	19.9	1.14
Truck #2 (GFI)	19.8	0.94
Truck #3 (IMPCO)		
Base Catalyst	23.5	0.97
Engle. Catalyst	n/a	n/a
Truck #4 (VIALLE)	23.1	1.10
MEAN (#1 incl.)	**22.8**	**1.00**
STANDARD DEVIATION (#1 incl.)	**2.83**	**0.10**
MEAN (#1 not included)	**22.1**	**1.00**
STANDARD DEVIATION (#1 not included)	**2.03**	**0.09**

APPENDIX B:

Raw Experimental Results

This appendix gives the raw experimental results from the multi-mode tests and the wide-open throttle tests.

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #1 : BASELINE  DOWNSTREAM     GASOLINE
--------------------------------------------------------------------------------------------
Mode Power  Vel. Fuel   Air   CO   CO2  NOx   RHC    CH4     O2    H/C  AFmas  AFem Repeats
      kW   km/h  g/s    g/s   %     %   ppm   ppm    ppm      %
--------------------------------------------------------------------------------------------
A      0.0   0.0  0.96  12.2 1.36 12.6  48.0  915.2   97.9   1.48  2.02  13.2   14.7   7
B     12.2  42.5  1.44  23.4 0.04 13.4  11.5   31.8    0.0   0.02  2.69  16.3   15.6   6
C     21.6  73.8  2.37  36.5 0.09 13.3  33.5   27.1    0.0   0.01  2.70  15.4   15.6   4
D      6.9  41.4  1.29  19.5 0.01 13.4   0.0    3.2    0.0   0.00  2.66  15.1   15.6   3
E      3.2  39.2  0.94  16.2 0.01 13.6  78.8    7.4    0.0   0.03  2.59  17.1   15.5   2
F     20.5  35.4  2.24  33.8 0.07 13.4  34.5   28.1    0.0   0.01  2.64  15.1   15.5   2
G     14.9  72.1  2.22  34.6 0.04 13.4   8.5   10.7    0.0   0.00  2.71  15.6   15.6   3
H     30.9  72.4  3.16  48.0 0.03 13.4  14.6    8.8    0.0   0.00  2.69  15.2   15.6   5
I     21.0  60.3  2.29  35.6 0.11 13.3  14.2   23.2    0.0   0.00  2.71  15.5   15.6   3
J     12.9  62.1  1.88  29.2 0.03 13.4   0.1    9.1    0.0   0.00  2.71  15.5   15.6   3
K      7.1  59.2  1.45  24.0 0.01 13.3   6.1    1.3    0.0   0.00  2.73  16.5   15.7   2
L     32.6  43.8  3.31  50.1 0.02 13.4  11.4    4.2    0.0   0.00  2.71  15.1   15.6   2
M     12.6  24.3  1.69  26.2 0.11 13.3   9.2   42.3    0.0   0.00  2.72  15.5   15.6   3
N     20.6  24.0  2.27  35.3 0.11 13.3  37.6   29.0    0.0   0.00  2.71  15.6   15.6   2
O      7.1  25.8  1.07  17.6 0.01 13.3   0.0    9.4    0.0   0.00  2.77  16.5   15.7   3
P      0.0   0.0  0.44   7.3 0.03 13.3   0.0   12.1    0.0   0.00  2.74  16.7   15.7   2
--------------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #1 : NO SPARK ADVANCE  DOWNSTREAM     NATURAL GAS
------------------------------------------------------------------------------------------
Mode Power  Vel. Fuel  Air   CO   CO2  NOx   RHC    CH4      O2     H/C  AFmas  AFem Repeats
       kW   km/h g/s   g/s   %      %  ppm   ppm    ppm       %
------------------------------------------------------------------------------------------
A      0.0   0.0 0.73  13.1 0.53 10.7  36.8  150.6 2014.0   1.391  3.60  18.0   17.2    3
B     12.5  43.0 1.41  25.3 0.01 10.4 240.2    0.8  765.0   1.825  3.97  18.0   18.5    2
C     21.4  72.6 2.42  42.1 0.01 10.5 388.5    0.0  317.0   1.554  4.01  17.4   18.4    1
D      6.5  39.0 0.94  18.5 0.01 10.2 112.4    0.0  618.0   2.078  4.00  19.7   18.8    2
E      3.5  37.8 0.90  16.4 0.00  9.9  46.5   13.1  900.0   2.605  4.03  18.4   19.3    4
F     20.6  35.5 2.18  41.2 0.01 10.1 219.2    0.0  401.0   2.329  4.02  18.9   19.1    2
G     14.4  71.3 1.94  35.4 0.01 10.0 200.6    0.0  419.0   2.413  4.02  18.2   19.1    2
H     27.2  70.3 2.49  42.5 0.01 14.0 414.0    2.0    0.0   0.017  2.31  17.1   15.1    2
I     19.9  59.7 1.95  37.4 0.01  9.9 289.8    0.0  467.0   1.655  4.49  19.2   19.0    2
J     13.5  60.9 1.73  31.9 0.00  9.8 224.3    0.0  535.0   2.262  4.34  18.4   19.4    2
K      7.6  59.9 1.39  26.5 0.00  9.7 121.7    0.0  575.0   2.378  4.35  19.1   19.5    2
L     31.0  43.7 3.25  58.4 0.00 10.2 346.0    0.0   80.0   1.076  4.53  18.0   18.5    2
M     12.3  24.9 1.43  29.0 0.00  9.5 174.8    0.0  579.0   1.939  4.80  20.4   19.5    2
N     20.7  23.7 2.31  42.3 0.00  9.6 209.0    0.0  442.0   1.950  4.66  18.3   19.4    2
O      6.5  27.5 0.86  18.3 0.00  9.7  82.7    0.0 1087.0   2.327  4.38  21.4   19.4    2
P      0.0   0.0 0.46  11.0 0.00 10.8  39.7    0.0 1479.0   0.436  4.28  25.0   17.6    2
------------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #1 : CONVERTED  DOWNSTREAM     GASOLINE
------------------------------------------------------------------------------------
Mode Power  Vel. Fuel  Air   CO   CO2  NOx   RHC   CH4    O2    H/C  AFmas  AFem Repeats
      kW   km/h  g/s   g/s   %     %   ppm   ppm   ppm     %
------------------------------------------------------------------------------------
A     0.0   0.0 1.71  12.7 0.80 11.3  69.1 627.4   0.0  3.878 1.88  11.4  17.6   3
B    12.8  43.3 1.58  24.6 0.09 13.1 151.5 106.5   0.0  0.115 2.73  15.6  15.6   2
C    21.4  74.9 2.58  39.9 0.09 12.8  39.9  33.2   0.0  0.011 3.00  15.5  15.9   2
D     6.3  39.6 1.05  18.0 0.02 12.7   0.0  20.3   0.0  0.006 3.06  17.1  16.0   2
E     3.0  36.0 0.82  14.6 0.01 12.6   0.0  19.5   0.0  0.003 3.13  17.8  16.1   3
F    20.2  35.4 2.14  32.5 0.02 12.7   4.8  11.1   0.0  0.002 3.10  15.2  16.1   4
G    14.3  69.8 2.07  31.6 0.03 12.7  10.4  22.2   0.0  0.009 3.09  15.3  16.1   2
H    26.8  67.8 2.73  41.1 0.05 12.7  31.5  17.4   0.0  0.002 3.04  15.0  16.0   2
I    21.1  59.4 2.36  33.9 0.01 12.7  53.3  15.3   0.0  0.001 3.05  14.3  16.0   2
J    12.7  61.5 1.80  27.9 0.01 12.7 141.0   9.5   0.0  0.007 3.10  15.6  16.1   2
K     7.1  57.9 1.33  22.7 0.01 12.6 181.5  13.0   0.0  0.013 3.16  17.1  16.2   2
L    37.5  47.3 3.54  55.5 0.01 12.6 927.9   2.7   0.0  0.103 3.07  15.7  16.2   1
M    12.8  24.3 1.41  24.1 0.02 12.5   8.9  29.8   0.0  0.003 3.22  17.1  16.2   2
N    22.5  24.3 2.30  41.0 0.01 12.7 368.0   8.1   0.0  0.004 3.09  17.8  16.1   2
O     7.0  27.0 0.92  16.6 0.02 12.5   0.6  18.3   0.0  0.001 3.18  17.9  16.2   2
P     0.0   0.0 0.42   9.3 0.03 12.6   0.0  63.9   0.0  0.000 3.13  22.4  16.1   2
------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #1 : MIXER ADJUSTED  DOWNSTREAM     NATURAL GAS
------------------------------------------------------------------------------------------
Mode Power  Vel. Fuel   Air   CO   CO2  NOx   RHC    CH4     O2    H/C  AFmas  AFem Repeats
      kW   km/h  g/s    g/s   %     %   ppm   ppm    ppm      %
------------------------------------------------------------------------------------------
A     0.0   0.0 0.00    0.0 0.00  0.0   0.0   0.0    0.0   0.000  0.00   0.0   0.0   0
B    12.0  40.8 1.34   23.2 0.00 10.3 220.8   0.0  783.5   2.086  3.98  17.3  18.8   4
C    20.9  72.3 2.35   38.7 0.00 10.7 424.6   0.0  391.0   1.420  3.91  16.5  18.2   4
D     7.3  41.1 1.07   17.9 0.00 10.5 143.3   0.0  671.0   1.629  4.05  16.7  18.4   2
E     2.6  36.6 0.80   13.6 0.00 10.4  62.1   0.0  988.0   1.670  4.05  17.1  18.4   2
F    21.6  36.1 2.21   36.1 0.01 10.9 410.2   0.0  460.0   1.136  3.96  16.4  17.9   2
G    14.2  69.7 1.93   31.4 0.01 10.7 289.1   0.0  363.0   1.451  3.95  16.3  18.2   2
H    27.1  66.6 2.58   40.9 0.01 11.1 547.7   0.0  442.0   0.865  3.89  15.9  17.7   2
I    18.8  56.7 1.96   31.8 0.01 10.7 378.3   0.0  452.0   1.501  3.95  16.2  18.3   2
J    13.4  60.6 1.74   28.4 0.01 10.5 257.8   0.0  485.0   1.746  3.99  16.3  18.5   2
K     6.9  59.8 1.33   23.0 0.01 10.2 121.4   0.0  568.0   2.087  4.04  17.3  18.9   2
L    33.5  45.2 3.53   53.5 0.01 11.5 165.7   0.0  124.0   0.148  3.86  15.2  17.1   2
M    12.7  24.4 1.52   26.6 0.00 10.3 258.9   0.0  378.0   1.631  4.17  17.5  18.6   2
N    20.1  23.9 2.28   36.0 0.00 10.7 330.4   0.0  413.0   1.193  4.06  15.8  18.1   2
O     6.3  25.2 0.94   15.8 0.00 10.2 142.9   0.0  918.0   1.592  4.26  16.8  18.6   2
P     0.0   0.0 0.38    9.7 0.10 11.5   0.0   0.0 1618.0   0.266  3.73  25.8  16.8   2
------------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #1 : SPARK ADVANCED  DOWNSTREAM     NATURAL GAS
-----------------------------------------------------------------------------------------------
Mode Power  Vel. Fuel  Air   CO   CO2  NOx   RHC    CH4     O2    H/C  AFmas  AFem Repeats
      kW   km/h  g/s   g/s   %     %   ppm   ppm    ppm      %
-----------------------------------------------------------------------------------------------
A     0.0   0.0 0.75  14.2 0.31  9.5  82.7  318.7 6760.0  2.700  4.09  19.0   18.3   4
B    12.4  42.9 1.35  25.1 0.01  9.9 609.2    0.0  929.0  2.060  4.28  18.6   19.0   4
C    20.4  70.6 2.24  39.8 0.01 10.5 370.0    5.0  547.0  2.134  3.79  17.8   18.6   4
D     7.0  40.5 0.94  20.5 0.01  9.9 259.0    0.0 1008.0  3.048  3.82  21.8   19.4   4
E     3.6  35.4 0.85  15.8 0.01 10.1  90.3    2.8 1175.0  2.716  3.80  18.6   19.1   4
F    21.2  37.8 2.01  37.3 0.01 10.2 452.2    0.0  761.0  2.395  3.85  18.6   18.9   4
G    14.1  70.7 1.80  34.2 0.01 10.1 332.1    0.0  672.0  2.633  3.85  19.0   19.1   4
H    27.0  70.8 2.59  45.6 0.01 10.4 331.4    3.4  612.0  2.058  3.86  17.6   18.6   4
I    20.0  57.3 1.89  35.2 0.01 10.4 328.4    1.0  728.0  2.079  3.89  18.6   18.6   2
J    13.4  61.3 1.61  30.4 0.01 10.1 272.5    0.0  760.0  2.555  3.85  18.9   19.0   2
K     7.2  60.6 1.29  24.7 0.01 10.1 366.8    0.0  811.0  2.643  3.84  19.1   19.1   2
L    31.5  43.1 2.98  53.1 0.01  9.7 984.4    0.7  357.0  1.251  4.91  17.8   19.1   2
M    12.8  25.1 1.42  27.1 0.01 10.4 373.6    0.0  479.0  2.148  3.85  19.2   18.7   2
N    20.7  24.0 1.97  37.4 0.01 10.4 506.4    0.0  768.0  2.168  3.83  19.0   18.7   2
O     6.9  27.3 0.83  17.8 0.01 10.3 203.4    0.0  896.0  2.291  3.80  21.3   18.7   2
P     0.0   0.0 0.42   9.9 0.01 11.5  58.2    0.0 1346.0  0.384  3.77  24.3   17.0   2
-----------------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #2 : CONVERTED  DOWNSTREAM     NATURAL GAS
-----------------------------------------------------------------------------------------
Mode Power  Vel. Fuel  Air   CO   CO2  NOx   RHC   CH4     O2     H/C   AFmas  AFem Repeats
      kW   km/h  g/s   g/s   %     %   ppm   ppm   ppm      %
-----------------------------------------------------------------------------------------
A     0.0   0.0  0.64  10.9 0.28  7.8  48.9  121.1 1763.6  3.293 %51.61  17.2   23.1   5
B    14.1  51.6  1.78  28.1 0.02 11.2 305.5   28.5  739.0  0.632  3.96  15.8   17.5   2
C    25.1  88.4  3.03  51.5 0.01 10.8 285.7   16.1    0.0  1.389  3.96  17.0   18.2   2
D     8.1  50.3  1.24  20.8 0.01 11.5 149.1    3.3  260.0  0.130  3.97  16.7   17.2   2
E     4.3  46.5  1.05  16.6 0.01 11.6   4.9    8.0    0.0  0.002  3.95  15.7   17.1   2
F    23.7  47.1  2.12  35.1 0.01 11.0 346.0   13.6  249.0  0.968  3.98  16.6   17.9   2
G    14.7  86.6  2.32  40.0 0.01 10.9 198.2   16.5    0.0  1.218  3.96  17.2   18.1   2
H    31.7  85.4  3.32  56.3 0.01 10.8 296.8   14.0    0.0  1.411  3.95  16.9   18.2   2
I    23.6  72.8  2.48  42.7 0.01 10.9 297.4    9.4    0.0  1.162  3.98  17.2   18.1   2
J    15.1  74.1  2.04  34.4 0.01 10.8 236.5    4.7  198.0  1.043  4.15  16.9   18.1   4
K     7.5  72.1  1.58  26.6 0.01 11.2 161.6    4.2  185.0  0.646  3.97  16.9   17.6   2
L    34.1  58.2  3.26  54.7 0.01 10.9 281.3   13.3    0.0  1.280  3.92  16.8   18.1   2
M    13.4  28.7  1.48  24.7 0.01 11.4 447.2    4.5  269.0  0.422  3.91  16.7   17.4   2
N    23.5  30.3  2.39  41.7 0.01 11.0 246.4   11.7  162.0  1.133  3.91  17.5   17.9   2
O     7.6  33.5  1.00  17.6 0.01 11.7   0.1   11.4    0.0  0.000  3.87  17.6   17.0   2
P     0.0   0.0  0.40   6.7 0.02 11.7   0.0   15.1   64.5  0.000  3.86  16.6   17.0   2
-----------------------------------------------------------------------------------------
```

ANALYSIS.BAS: OCN/MDC - JAN 22 94: RAW EXPERIMENTAL RESULTS

TRUCK #2 : CONVERTED DOWNSTREAM GASOLINE

Mode	Power kW	Vel. km/h	Fuel g/s	Air g/s	CO %	CO2 %	NOx ppm	RHC ppm	CH4 ppm	O2 %	H/C	AFmas	AFem	Repeats
A	0.0	0.0	0.78	10.3	2.19	12.3	67.9	856.6	52.0	1.130	2.06	13.4	14.4	6
B	13.0	51.0	1.76	25.9	0.39	14.5	230.6	166.5	0.0	0.291	1.91	14.7	14.5	6
C	24.6	87.1	3.05	46.1	0.01	14.7	161.4	12.1	0.0	0.025	2.01	15.1	14.7	5
D	7.7	50.1	1.36	20.8	0.00	14.6	0.9	4.6	0.0	0.004	2.10	15.3	14.8	5
E	4.2	48.2	1.22	17.1	0.01	14.8	0.0	5.0	0.0	0.007	1.98	14.1	14.7	2
F	24.3	46.3	2.27	32.7	0.07	14.3	44.7	67.1	0.0	0.004	2.25	14.5	15.0	3
G	16.4	86.0	2.56	37.8	0.01	14.8	70.5	6.8	0.0	0.002	2.02	14.8	14.7	2
H	31.9	84.3	3.40	50.3	0.01	14.8	40.0	5.3	0.0	0.000	2.01	14.8	14.7	2
I	23.9	71.0	2.58	38.9	0.03	13.8	15.7	9.1	0.0	0.000	2.50	15.1	15.4	2
J	15.1	73.7	2.23	32.8	0.01	14.8	9.8	3.7	0.0	0.001	2.02	14.7	14.7	2
K	7.7	75.0	1.86	27.6	0.00	14.8	27.7	2.9	0.0	0.000	2.01	14.8	14.7	2
L	38.0	61.7	3.68	53.6	0.01	14.2	589.4	1.7	0.0	0.035	2.30	14.6	15.2	3
M	13.6	29.4	1.67	24.2	0.01	14.8	8.8	5.5	0.0	0.000	2.01	14.5	14.7	2
N	23.3	29.7	2.49	37.5	0.01	14.8	81.6	2.0	0.0	0.000	2.01	15.0	14.7	2
O	8.0	33.7	1.20	17.2	0.01	14.8	0.0	4.8	0.0	0.000	2.00	14.3	14.7	2
P	0.0	0.0	0.47	6.9	0.04	14.8	0.0	140.2	54.0	0.000	1.99	14.7	14.6	4

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #2 : CONVERTED  DOWNSTREAM     NATURAL GAS
----------------------------------------------------------------------------------------
Mode Power  Vel. Fuel   Air   CO   CO2  NOx   RHC    CH4     O2     H/C   AFmas  AFem Repeats
       kW   km/h  g/s   g/s   %     %   ppm   ppm    ppm      %
----------------------------------------------------------------------------------------
A      0.0   0.0 0.64  10.9 0.28  7.8  48.9  121.1 1763.6   3.293  %51.61  17.2   23.1   5
B     14.1  51.6 1.78  28.1 0.02 11.2 305.5   28.5  739.0   0.632  3.96  15.8   17.5   2
C     25.1  88.4 3.03  51.5 0.01 10.8 285.7   16.1    0.0   1.389  3.96  17.0   18.2   2
D      8.1  50.3 1.24  20.8 0.01 11.5 149.1    3.3  260.0   0.130  3.97  16.7   17.2   2
E      4.3  46.5 1.05  16.6 0.01 11.6   4.9    8.0    0.0   0.002  3.95  15.7   17.1   2
F     23.7  47.1 2.12  35.1 0.01 11.0 346.0   13.6  249.0   0.968  3.98  16.6   17.9   2
G     14.7  86.6 2.32  40.0 0.01 10.9 198.2   16.5    0.0   1.218  3.96  17.2   18.1   2
H     31.7  85.4 3.32  56.3 0.01 10.8 296.8   14.0    0.0   1.411  3.95  16.9   18.2   2
I     23.6  72.8 2.48  42.7 0.01 10.9 297.4    9.4    0.0   1.162  3.98  17.2   18.1   2
J     15.1  74.1 2.04  34.4 0.01 10.8 236.5    4.7  198.0   1.043  4.15  16.9   18.1   4
K      7.5  72.1 1.58  26.6 0.01 11.2 161.6    4.2  185.0   0.646  3.97  16.9   17.6   2
L     34.1  58.2 3.26  54.7 0.01 10.9 281.3   13.3    0.0   1.280  3.92  16.8   18.1   2
M     13.4  28.7 1.48  24.7 0.01 11.4 447.2    4.5  269.0   0.422  3.91  16.7   17.4   2
N     23.5  30.3 2.39  41.7 0.01 11.0 246.4   11.7  162.0   1.133  3.91  17.5   17.9   2
O      7.6  33.5 1.00  17.6 0.01 11.7   0.1   11.4    0.0   0.000  3.87  17.6   17.0   2
P      0.0   0.0 0.40   6.7 0.02 11.7   0.0   15.1   64.5   0.000  3.86  16.6   17.0   2
----------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #3 : BASE CATALYST  DOWNSTREAM     NATURAL GAS
------------------------------------------------------------------------------------------
Mode Power  Vel. Fuel   Air   CO   CO2  NOx    RHC    CH4      O2      H/C  AFmas  AFem Repeats
      kW    km/h  g/s   g/s   %     %   ppm    ppm    ppm      %
------------------------------------------------------------------------------------------
A     0.0   0.0  0.69  12.0 0.43 10.8  61.2   46.3 1613.0   2.347  3.28  17.4   17.8   2
B    13.3  52.9  1.85  30.6 0.09 11.6 258.5   57.7  751.0   0.423  3.75  16.5   17.1   2
C    25.1  88.7  3.12  49.3 0.14 11.5 105.9   38.1  131.0   0.100  3.91  15.8   17.1   3
D     7.7  48.2  1.29  20.8 0.01 11.6  83.2    8.4    0.0   0.180  3.89  16.1   17.2   2
E     3.9  45.7  1.09  17.2 0.01 11.5  36.7   21.4  188.0   0.269  3.97  15.8   17.3   3
F    20.9  40.0  1.92  30.0 0.01 11.5 327.9   30.9  100.0   0.226  3.97  15.6   17.3   2
G    15.4  86.7  2.36  39.8 0.01 11.6  47.8    5.3    0.0   0.105  3.91  16.9   17.2   3
H    31.1  85.7  3.33  53.0 0.04 11.7  57.9   23.7    0.0   0.093  3.86  15.9   17.1   3
I    22.9  71.0  2.48  39.9 0.01 11.7 130.2    7.8    0.0   0.124  3.87  16.1   17.1   3
J    14.9  74.8  2.27  35.2 0.01 11.9  60.5   26.5    0.0   0.134  3.68  15.6   16.9   3
K     8.2  75.9  1.88  29.7 0.01 11.9  68.7   12.8    0.0   0.162  3.70  15.8   17.0   3
L    36.4  60.3  3.43  55.0 0.01 11.8 341.3   17.1    0.0   0.164  3.72  16.0   17.0   2
M    14.9  32.1  1.61  26.5 0.01 11.6 499.8   37.0  243.0   0.456  3.76  16.5   17.2   3
N    23.7  30.7  2.43  38.7 0.01 11.8 143.6   19.0    0.0   0.128  3.78  15.9   17.0   3
O     7.6  33.6  1.14  18.2 0.01 11.6 153.2   34.0  205.0   0.334  3.78  16.0   17.1   3
P     0.0   0.0  0.38   7.0 0.00  9.4  26.6   15.5 2234.0   4.646  3.60  18.7   20.9   3
------------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #3 : ENGLEHARD CATALYST  DOWNSTREAM     GASOLINE
---------------------------------------------------------------------------------------------
Mode Power  Vel. Fuel   Air   CO   CO2  NOx   RHC    CH4     O2     H/C  AFmas  AFem Repeats
      kW   km/h  g/s   g/s    %     %   ppm   ppm    ppm     %
---------------------------------------------------------------------------------------------
A     0.0   0.0  1.40  12.8 1.35 12.2  89.8  557.9    0.0   3.188  1.64  10.2   16.1   2
B    12.6  50.8  1.85  27.3 0.01 14.0  32.8    2.1    0.0   0.109  2.40  14.8   15.3   2
C    24.0  90.0  3.21  49.2 0.01 13.9 364.9   15.0    0.0   0.107  2.40  15.3   15.3   2
D     7.9  48.7  1.45  22.5 0.01 13.9   2.5    5.9    0.0   0.100  2.43  15.6   15.4   2
E     3.9  47.0  1.17  18.5 0.02 13.9   0.0   24.1    0.0   0.104  2.41  15.8   15.3   2
F    23.2  45.6  2.24  33.9 0.01 13.9   7.7    9.7    0.0   0.095  2.45  15.1   15.4   2
G    16.4  87.4  2.58  41.0 0.01 13.7 245.0   18.6    0.0   0.119  2.55  15.9   15.5   3
H    32.0  86.5  3.43  54.6 0.01 13.7 443.4    7.9    0.0   0.113  2.54  15.9   15.5   2
I    23.2  72.1  2.66  40.7 0.02 13.5   2.4   35.8    0.0   0.100  2.64  15.4   15.6   3
J    15.5  75.3  2.34  35.7 0.01 13.5  30.1    6.8    0.0   0.100  2.65  15.2   15.7   2
K     8.2  74.4  1.95  29.5 0.03 13.7   1.7   42.8    0.0   0.109  2.54  15.1   15.5   3
L    36.9  59.9  3.24  49.9 0.01 15.0 104.5    5.5    0.0   0.102  1.87  15.4   14.6   3
M    14.1  30.5  1.71  25.4 0.01 15.0 119.8   26.0    0.0   0.105  1.87  14.9   14.6   3
N    23.8  30.1  2.57  39.3 0.01 15.0 206.2   10.5    0.0   0.098  1.87  15.3   14.6   3
O     7.5  33.9  1.16  18.3 0.01 14.9 119.2   39.7    0.0   0.209  1.88  15.8   14.7   3
P     0.0   0.0  0.39   6.4 0.01 14.5  41.2   15.5    0.0   0.746  1.89  16.8   15.1   3
---------------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #4 : CONVERTED  DOWNSTREAM     GASOLINE
-------------------------------------------------------------------------------------
Mode Power  Vel. Fuel  Air   CO   CO2  NOx   RHC    CH4     O2    H/C  AFmas  AFem Repeats
       kW   km/h  g/s   g/s   %     %  ppm   ppm    ppm     %
-------------------------------------------------------------------------------------
A     0.0   0.0  1.03  12.7 2.20 12.9 120.9  599.7   0.0   0.753  1.92  12.3   14.1   2
B    12.8  51.9  1.88  25.6 0.01 15.6 312.3   21.4   0.0   0.120  1.60  13.6   14.2   2
C    24.4  88.9  3.29  44.8 0.01 15.7  37.8   24.7   0.0   0.094  1.57  13.6   14.1   3
D     7.5  49.2  1.42  19.5 0.01 15.7   1.2    9.6   0.0   0.091  1.60  13.8   14.2   3
E     4.3  47.3  1.15  17.1 0.01 15.6 310.9   32.9   0.0   0.127  1.61  14.9   14.2   3
F    21.1  45.3  2.03  29.1 0.01 15.7  13.2   17.5   0.0   0.089  1.60  14.4   14.2   2
G    16.2  88.4  2.70  37.8 0.01 15.7 100.8   20.1   0.0   0.093  1.58  14.0   14.2   3
H    31.6  86.5  3.44  48.7 0.01 15.7 263.7   12.3   0.0   0.092  1.59  14.2   14.2   2
I    23.1  71.6  2.62  37.0 0.01 15.0  78.3   25.6   0.0   0.094  1.92  14.1   14.6   3
J    14.7  74.4  2.31  31.6 0.01 15.7   9.2   16.1   0.0   0.092  1.58  13.7   14.2   2
K     8.1  74.9  2.00  27.1 0.05 15.7  39.3   23.8   0.0   0.091  1.59  13.6   14.2   3
L    35.5  59.3  3.16  43.9 0.01 15.6 121.5   11.1   0.0   0.091  1.61  13.9   14.2   2
M    14.1  30.3  1.66  23.5 0.07 15.6  28.0   62.9   0.0   0.092  1.60  14.2   14.1   3
N    24.3  31.4  2.61  36.4 0.03 15.6  33.9   30.5   0.0   0.090  1.61  13.9   14.2   2
O     7.4  32.8  1.13  16.5 0.02 15.6   5.7   69.9   0.0   0.094  1.61  14.6   14.2   3
P     0.0   0.0  0.41   5.9 0.03 15.7   0.0   83.5   0.0   0.089  1.59  14.5   14.1   3
-------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #4     : CONVERTED  DOWNSTREAM      NATURAL GAS
-----------------------------------------------------------------------------------------------
Mode Power  Vel. Fuel   Air   CO    CO2  NOx    RHC    CH4      O2      H/C  AFmas   AFem Repeats
      kW   km/h  g/s    g/s   %      %   ppm    ppm    ppm       %
-----------------------------------------------------------------------------------------------
A     0.0    0.0  0.73  11.3 0.22 10.9  65.0  108.2 1098.0   1.338   3.70  15.5    17.6   3
B    13.7   52.1  1.76  27.7 0.01 10.8 431.6   46.2  319.0   1.360   3.87  15.7    18.0   2
C    24.7   91.3  3.20  47.6 0.12 11.3  24.4   57.5  112.0   0.095   4.02  14.9    17.1   3
D     7.6   48.5  1.27  20.4 0.01 11.2 151.8   46.3    0.0   0.305   4.06  16.0    17.4   3
E     4.3   47.6  1.07  17.9 0.01 10.8 122.7   38.8  341.0   1.237   4.00  16.8    18.1   3
F    23.1   44.5  2.48  39.0 0.01 10.8 466.3   51.9    0.0   0.994   4.05  15.7    18.0   2
G    16.1   88.1  2.63  39.8 0.01 11.3 374.2   41.2    0.0   0.268   4.11  15.2    17.5   3
H    31.5   87.5  3.56  52.0 0.10 11.2  40.5   53.2  115.0   0.104   4.19  14.6    17.4   3
I    22.7   70.8  2.45  38.7 0.01 10.8 533.8   57.4    0.0   0.761   4.31  15.8    18.1   3
J    15.3   74.1  2.10  34.3 0.01 10.5 340.1   36.5    0.0   1.380   4.27  16.3    18.6   3
K     8.5   74.5  1.76  29.6 0.01 10.2 191.2   33.8    0.0   2.027   4.18  16.8    19.0   3
L    36.9   58.8  3.88  58.7 0.01 11.0 334.9   17.5    0.0   0.185   4.34  15.1    17.7   2
M    14.8   31.9  1.67  27.2 0.01 10.3 348.4   54.6    0.0   1.715   4.23  16.4    18.8   3
N    24.5   31.7  2.85  45.1 0.01 10.7 379.9   42.1    0.0   0.948   4.32  15.8    18.2   3
O     7.6   33.8  1.12  17.7 0.01 10.6 237.4   20.2  520.0   0.993   4.34  15.8    18.2   3
P     0.0    0.0  0.42   6.3 0.01 10.9  42.5   15.0  890.0   0.416   4.38  15.5    17.8   2
-----------------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #1 : BASELINE  UPSTREAM       GASOLINE
-------------------------------------------------------------------------------------------
Mode Power  Vel. Fuel  Air   CO   CO2  NOx   RHC    CH4     O2    H/C  AFmas  AFem Repeats
      kW   km/h  g/s   g/s   %     %   ppm   ppm    ppm      %
-------------------------------------------------------------------------------------------
A      0.0   0.0  0.00   0.0 0.00  0.0   0.0    0.0    0.0  0.00  0.00   0.0    0.0   0
B     11.8  41.6  1.52  23.0 0.78 12.8 598.7  208.0   30.0  0.66  2.43  15.1   15.3   1
C      0.0   0.0  0.00   0.0 0.00  0.0   0.0    0.0    0.0  0.00  0.00   0.0    0.0   0
D      0.0   0.0  0.00   0.0 0.00  0.0   0.0    0.0    0.0  0.00  0.00   0.0    0.0   0
E      0.0   0.0  0.00   0.0 0.00  0.0   0.0    0.0    0.0  0.00  0.00   0.0    0.0   0
F      0.0   0.0  0.00   0.0 0.00  0.0   0.0    0.0    0.0  0.00  0.00   0.0    0.0   0
G     14.8  72.3  2.19  34.5 0.53 13.0 572.9  149.2    0.0  0.39  2.58  15.7   15.5   2
H      0.0   0.0  0.00   0.0 0.00  0.0   0.0    0.0    0.0  0.00  0.00   0.0    0.0   0
I      0.0   0.0  0.00   0.0 0.00  0.0   0.0    0.0    0.0  0.00  0.00   0.0    0.0   0
J      0.0   0.0  0.00   0.0 0.00  0.0   0.0    0.0    0.0  0.00  0.00   0.0    0.0   0
K      0.0   0.0  0.00   0.0 0.00  0.0   0.0    0.0    0.0  0.00  0.00   0.0    0.0   0
L      0.0   0.0  0.00   0.0 0.00  0.0   0.0    0.0    0.0  0.00  0.00   0.0    0.0   0
M      0.0   0.0  0.00   0.0 0.00  0.0   0.0    0.0    0.0  0.00  0.00   0.0    0.0   0
N     19.5  23.1  2.25  34.3 0.63 12.7 984.4  205.3    0.0  0.46  2.63  15.2   15.5   2
O      0.0   0.0  0.00   0.0 0.00  0.0   0.0    0.0    0.0  0.00  0.00   0.0    0.0   0
P      0.0   0.0  0.45   7.4 0.34 12.8  95.9  389.6   63.0  0.58  2.69  16.3   15.6   3
-------------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #1 : NO SPARK ADVANCE  UPSTREAM       NATURAL GAS
-----------------------------------------------------------------------------------------------
Mode Power  Vel. Fuel  Air   CO   CO2  NOx   RHC    CH4     O2    H/C  AFmas  AFem Repeats
      kW   km/h  g/s   g/s   %     %   ppm   ppm    ppm     %
-----------------------------------------------------------------------------------------------
A     0.0   0.0 0.00   0.0 0.00  0.0   0.0    0.0    0.0  0.000  0.00   0.0   0.0   0
B    12.7  43.1 1.41  25.2 0.05 10.1 301.7    9.6  709.0  2.006  4.14  17.9  18.8   2
C    20.2  71.3 2.32  40.3 0.06 10.3 396.5    6.4  502.0  1.575  4.12  17.4  18.5   2
D     6.6  39.8 1.06  19.1 0.06  9.8  97.8   10.2  870.0  2.634  4.04  18.0  19.3   2
E     3.4  36.3 0.84  15.9 0.06  9.9  59.3   16.4 1006.5  2.514  4.08  18.9  19.2   4
F    20.9  35.6 2.27  41.0 0.04 10.0 216.5    3.5  518.0  2.314  4.04  18.0  19.0   1
G    15.0  73.1 2.02  36.8 0.06  9.9 196.8    6.7  493.0  2.329  4.17  18.2  19.2   2
H    27.4  71.0 2.50  42.7 0.46 13.4 865.2  170.6   47.0  0.446  2.31  17.1  15.2   2
I    20.4  59.2 1.98  37.9 0.05  9.9 281.9    8.1  557.0  2.052  4.30  19.2  19.1   2
J    13.4  60.7 1.73  32.0 0.04  9.8 191.7    5.0  644.0  2.358  4.25  18.5  19.3   2
K     7.5  59.7 1.43  26.1 0.05  9.7 105.7    3.1  697.0  2.403  4.30  18.3  19.4   2
L    33.1  41.6 3.40  59.2 0.04 10.4 965.1    2.7  367.0  1.291  4.22  17.4  18.4   2
M    12.4  24.7 1.50  29.5 0.04  9.4 166.7    6.1  726.0  2.252  4.68  19.7  19.7   2
N    21.0  24.2 2.32  43.3 0.03  9.7 211.6    1.0  588.0  2.006  4.53  18.6  19.3   2
O     7.0  26.3 1.06  18.8 0.04  9.6 102.0    0.7 1096.0  2.411  4.42  17.7  19.5   2
P     0.0   0.0 0.41  10.5 0.38 10.6  44.4   15.7 1424.0  0.784  4.04  26.1  17.4   2
-----------------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #1 : CONVERTED  UPSTREAM        GASOLINE
-------------------------------------------------------------------------------------
Mode Power  Vel. Fuel   Air   CO   CO2  NOx   RHC     CH4     O2    H/C  AFmas  AFem Repeats
      kW   km/h  g/s    g/s   %     %   ppm   ppm     ppm     %
-------------------------------------------------------------------------------------
A     0.0   0.0 0.00    0.0 0.00  0.0   0.0    0.0     0.0  0.000  0.00   0.0    0.0   0
B    12.6  43.3 1.53   24.3 0.67 12.4 877.5  240.5     0.0  0.676  2.70  15.9   15.7   3
C    22.0  75.6 2.63   40.6 0.55 12.5 928.6  198.4     0.0  0.434  2.78  15.4   15.7   3
D     6.2  39.9 1.08   18.0 0.58 12.1 293.8  250.3     0.0  0.614  2.96  16.6   16.0   2
E     3.1  36.3 0.87   14.7 0.53 12.1 469.1  230.3     0.0  0.557  3.00  17.0   16.1   2
F    20.5  36.4 2.02   33.4 0.49 12.1 984.4  219.9     0.0  0.466  3.01  16.6   16.0   2
G    14.7  69.9 2.03   32.0 0.62 12.1 599.5  183.8     0.0  0.491  2.97  15.8   16.0   2
H    28.1  67.8 2.74   41.7 0.47 12.2 984.4  200.7     0.0  0.381  2.98  15.2   16.0   2
I    20.4  57.7 2.23   32.4 0.57 12.1 984.4  206.3     0.0  0.520  2.98  14.5   16.0   2
J    13.0  62.1 1.79   28.1 0.65 12.0 541.8  187.0     0.0  0.601  2.95  15.7   16.0   2
K     7.1  57.8 1.44   22.7 0.69 12.0 787.8  145.5     0.0  0.544  2.97  15.8   16.0   2
L    34.5  45.4 3.62   51.2 0.46 12.1 984.4  194.0     0.0  0.506  3.01  14.2   16.1   2
M    11.9  24.4 1.41   22.7 0.60 11.8 827.5  247.2     0.0  0.546  3.11  16.0   16.1   2
N    21.0  23.8 2.25   34.7 0.49 12.1 984.4  215.8     0.0  0.443  3.04  15.5   16.1   2
O     6.7  26.8 1.01   16.1 0.44 11.8 364.1  280.0     0.0  0.524  3.23  16.0   16.3   2
P     0.0   0.0 0.44    9.1 0.37 12.0  88.3  401.8     0.0  0.505  3.14  20.8   16.1   2
-------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #1 : MIXER ADJUSTED  UPSTREAM       NATURAL GAS
-----------------------------------------------------------------------------------------
Mode Power  Vel. Fuel  Air   CO   CO2  NOx   RHC    CH4      O2     H/C   AFmas  AFem Repeats
      kW   km/h  g/s   g/s   %     %  ppm   ppm    ppm       %
-----------------------------------------------------------------------------------------
A     4.0  14.3  0.91  16.6 0.11  9.7 122.0   0.0 2014.0   2.980  3.98   18.4   19.4   3
B    12.0  42.8  1.39  24.4 0.04 10.1 250.7   0.0  798.0   2.454  3.91   17.5   19.0   2
C    21.1  72.5  2.37  40.1 0.05 10.4 345.0   0.0  529.0   1.838  3.95   16.9   18.5   2
D     0.0   0.0  0.00   0.0 0.00  0.0   0.0   0.0    0.0   0.000  0.00    0.0    0.0   0
E     0.0   0.0  0.00   0.0 0.00  0.0   0.0   0.0    0.0   0.000  0.00    0.0    0.0   0
F     0.0   0.0  0.00   0.0 0.00  0.0   0.0   0.0    0.0   0.000  0.00    0.0    0.0   0
G     0.0   0.0  0.00   0.0 0.00  0.0   0.0   0.0    0.0   0.000  0.00    0.0    0.0   0
H     0.0   0.0  0.00   0.0 0.00  0.0   0.0   0.0    0.0   0.000  0.00    0.0    0.0   0
I     0.0   0.0  0.00   0.0 0.00  0.0   0.0   0.0    0.0   0.000  0.00    0.0    0.0   0
J     0.0   0.0  0.00   0.0 0.00  0.0   0.0   0.0    0.0   0.000  0.00    0.0    0.0   0
K     0.0   0.0  0.00   0.0 0.00  0.0   0.0   0.0    0.0   0.000  0.00    0.0    0.0   0
L     0.0   0.0  0.00   0.0 0.00  0.0   0.0   0.0    0.0   0.000  0.00    0.0    0.0   0
M     0.0   0.0  0.00   0.0 0.00  0.0   0.0   0.0    0.0   0.000  0.00    0.0    0.0   0
N     0.0   0.0  0.00   0.0 0.00  0.0   0.0   0.0    0.0   0.000  0.00    0.0    0.0   0
O     0.0   0.0  0.00   0.0 0.00  0.0   0.0   0.0    0.0   0.000  0.00    0.0    0.0   0
P     0.0   0.0  0.00   0.0 0.00  0.0   0.0   0.0    0.0   0.000  0.00    0.0    0.0   0
-----------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #1 : SPARK ADVANCED  UPSTREAM       NATURAL GAS
------------------------------------------------------------------------------------------
Mode Power  Vel. Fuel   Air   CO   CO2  NOx   RHC    CH4     O2    H/C  AFmas  AFem Repeats
      kW   km/h  g/s    g/s   %     %   ppm   ppm    ppm     %
------------------------------------------------------------------------------------------
A     0.0   0.0  0.00   0.0 0.00  0.0   0.0    0.0     0.0  0.000  0.00   0.0   0.0   0
B    12.2  42.1  1.28  24.5 0.05  9.3 915.1    0.5   922.0  2.240  4.72  19.1  19.7   2
C    20.6  70.3  2.24  39.8 0.05  9.4 984.4    8.6   733.0  2.164  4.74  17.8  19.7   2
D     6.9  39.7  0.96  19.5 0.06  8.9 236.8   13.0  1048.0  3.082  4.77  20.4  20.5   2
E     3.2  39.7  0.76  16.4 0.07  8.9  99.0   12.9  1198.0  2.851  4.89  21.5  20.4   2
F    20.6  35.9  2.02  36.8 0.04  9.1 984.4    5.8   790.0  2.450  4.88  18.2  20.1   2
G    14.2  70.7  1.87  34.2 0.06  8.9 652.1   17.1   761.0  2.693  4.94  18.3  20.4   2
H    27.2  71.4  2.55  46.1 0.05  9.2 984.4   24.5   700.0  2.078  4.93  18.1  19.8   2
I    20.4  58.4  1.98  35.9 0.06  9.3 984.4   16.7   750.0  2.187  4.80  18.2  19.7   2
J    13.6  62.2  1.62  30.8 0.06  9.1 849.9    5.8   792.0  2.565  4.80  19.0  20.1   2
K     7.3  60.6  1.28  24.6 0.07  8.9 349.8    3.7   866.0  2.717  4.96  19.3  20.4   2
L    33.4  42.7  3.05  55.2 0.06  9.6 984.4   22.5   620.0  1.363  4.86  18.1  19.0   1
M    12.5  24.4  1.37  27.0 0.06  9.1 976.3    6.9   865.0  2.454  4.79  19.7  20.0   2
N    21.5  25.2  2.05  37.8 0.05  9.3 984.4    4.7   768.0  2.056  4.82  18.4  19.6   2
O     6.6  26.3  0.84  17.7 0.06  9.1 179.8    4.9   915.0  2.540  4.82  21.4  20.0   2
P     0.0   0.0  0.41   9.8 0.33  9.7  66.7    9.1  1364.0  0.764  4.88  24.5  18.3   2
------------------------------------------------------------------------------------------
```

ANALYSIS.BAS: OCN/MDC - JAN 22 94: RAW EXPERIMENTAL RESULTS

TRUCK #2 : CONVERTED UPSTREAM GASOLINE

Mode	Power kW	Vel. km/h	Fuel g/s	Air g/s	CO %	CO2 %	NOx ppm	RHC ppm	CH4 ppm	O2 %	H/C	AFmas	AFem	Repeats
A	0.0	0.0	0.84	11.5	2.57	12.3	67.6	437.6	0.0	0.477	2.14	13.9	14.1	2
B	13.5	52.6	1.88	28.7	0.83	13.7	621.5	169.8	0.0	0.627	2.02	15.2	14.8	2
C	24.7	87.9	3.19	48.9	0.61	14.0	699.3	117.6	0.0	0.436	2.02	15.3	14.8	2
D	7.8	50.0	1.49	22.4	0.62	13.9	234.5	148.8	0.0	0.600	2.02	15.0	14.9	2
E	4.3	46.7	1.23	18.4	0.47	14.1	489.9	124.6	0.0	0.487	2.03	15.0	14.9	2
F	22.2	42.6	2.16	32.0	0.67	13.8	691.6	154.5	0.0	0.585	2.03	14.8	14.8	1
G	16.0	87.2	2.58	40.2	0.62	13.9	408.8	99.5	0.0	0.507	2.04	15.6	14.9	2
H	31.5	86.4	3.49	52.2	0.61	13.8	832.0	133.3	0.0	0.690	2.03	15.0	15.0	2
I	22.9	68.2	2.54	38.7	0.63	13.8	677.9	136.3	0.0	0.750	2.02	15.2	15.0	4
J	16.0	75.5	2.33	36.1	0.64	13.7	399.7	118.9	0.0	0.817	2.02	15.5	15.0	2
K	9.7	73.5	1.94	30.4	0.69	13.6	265.1	112.5	0.0	0.912	2.02	15.7	15.1	2
L	37.4	57.0	3.54	55.0	0.54	13.8	942.0	136.3	0.0	0.761	2.01	15.5	15.0	2
M	14.4	30.6	1.65	26.3	0.74	13.5	578.0	163.5	0.0	0.952	2.03	15.9	15.1	2
N	25.2	31.8	2.76	41.4	0.59	13.7	785.2	146.3	0.0	0.845	2.02	15.0	15.1	2
O	7.7	34.2	1.21	18.4	0.49	13.8	261.8	190.9	0.0	0.874	2.03	15.2	15.1	2
P	0.0	0.0	0.43	6.7	0.41	13.8	55.9	336.4	0.0	0.909	2.03	15.8	15.0	2

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #2 : CONVERTED  UPSTREAM       NATURAL GAS
-------------------------------------------------------------------------------
Mode Power  Vel. Fuel   Air   CO    CO2  NOx   RHC    CH4      O2     H/C  AFmas  AFem Repeats
      kW   km/h  g/s    g/s   %     %    ppm   ppm    ppm      %
-------------------------------------------------------------------------------
A     0.0   0.0  0.00   0.0 0.00   0.0   0.0    0.0     0.0   0.000  0.00   0.0    0.0   0
B    13.0  51.7  1.72  27.8 0.50 10.5 619.7   19.7   893.0   1.514  3.77  16.1   17.8   2
C    23.0  88.9  3.02  50.8 0.72  9.9 365.6   17.1   539.0   2.346  3.75  16.8   18.4   2
D     7.4  48.2  1.22  20.6 0.24 11.0 266.7   24.3   886.0   1.024  3.80  16.8   17.5   2
E     4.0  46.2  1.11  17.3 0.29 11.0 141.1   28.4 1015.0   1.026  3.78  15.7   17.5   3
F    22.5  43.8  2.35  39.9 0.82  9.9 390.7   12.7   734.0   2.291  3.73  17.0   18.3   2
G    15.7  83.5  2.43  40.6 0.68 10.0 283.3   16.0   635.0   2.309  3.73  16.8   18.4   2
H    30.8  86.3  3.30  56.6 0.78  9.8 371.7   17.2   566.0   2.431  3.75  17.2   18.5   2
I    23.0  71.1  2.46  42.0 0.76  9.9 432.4   21.1   684.0   2.308  3.74  17.1   18.4   2
J    15.1  73.7  2.00  35.3 0.61 10.1 324.8   17.9   671.0   2.106  3.75  17.6   18.3   2
K     8.2  71.9  1.70  28.0 0.40 10.6 241.6   20.9   635.0   1.556  3.76  16.5   17.9   2
L    37.2  58.2  3.51  60.5 0.91  9.7 310.9   16.3   594.0   2.536  3.69  17.3   18.4   2
M    14.4  30.3  1.54  26.6 0.48 10.6 625.2   12.6   857.0   1.583  3.72  17.3   17.8   2
N    23.7  30.9  2.40  41.7 0.90  9.8 330.4    6.7   726.0   2.364  3.72  17.4   18.3   2
O     7.2  32.9  1.07  17.7 0.24 11.0 320.7   25.2 1112.0   0.996  3.77  16.6   17.4   2
P     0.0   0.0  0.35   6.4 0.54 10.6  45.3   81.6 2099.0   1.486  3.73  18.3   17.5   2
-------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #3 : BASE CATALYST  UPSTREAM       GASOLINE
-----------------------------------------------------------------------------------------------
Mode Power  Vel.  Fuel  Air   CO   CO2  NOx    RHC    CH4     O2     H/C   AFmas  AFem Repeats
      kW    km/h  g/s   g/s   %     %   ppm    ppm    ppm      %
-----------------------------------------------------------------------------------------------
A     0.0   0.0  0.00   0.0 0.00  0.0   0.0    0.0    0.0   0.000  0.00   0.0    0.0   0
B    12.9  51.4  1.76  26.1 0.66 14.1 637.4  250.1    0.0   0.660  1.90  14.9   14.7   2
C    25.8  89.6  3.27  49.4 0.44 14.3 862.8  199.4    0.0   0.565  1.91  15.1   14.7   2
D     7.5  49.3  1.37  20.8 0.49 13.8 294.2  222.3    9.0   0.749  2.04  15.2   15.0   2
E     4.2  47.2  1.13  17.7 0.50 13.8 189.8  264.1   13.0   0.756  2.04  15.6   14.9   2
F    21.4  44.9  2.06  30.2 0.50 13.9 816.0  209.5    0.0   0.540  2.06  14.6   14.9   2
G    15.0  84.7  2.51  37.6 0.36 14.1 593.5  178.8    0.0   0.604  2.01  15.0   14.9   1
H    31.2  85.1  3.41  50.7 0.39 14.2 844.6  179.5    0.0   0.523  1.97  14.9   14.8   2
I    23.0  71.3  2.54  38.9 0.38 14.1 730.8  189.6    0.0   0.510  2.02  15.3   14.9   2
J    14.8  74.4  2.22  33.3 0.36 14.0 503.8  163.1    0.0   0.644  2.01  15.0   15.0   2
K     8.7  72.6  1.85  28.1 0.48 14.0 753.9  122.8    0.0   0.491  2.02  15.2   14.9   2
L    36.3  56.5  3.21  47.2 0.54 14.0 845.8  193.8    0.0   0.588  1.97  14.7   14.8   2
M    14.0  29.6  1.70  24.5 0.42 14.0 691.3  227.0    0.0   0.627  2.00  14.4   14.9   2
N    25.5  32.0  2.69  39.8 0.48 14.1 841.5  210.0    0.0   0.544  2.00  14.8   14.8   2
O     7.9  34.0  1.19  18.1 0.45 13.8 393.8  263.2    0.0   0.759  2.04  15.3   15.0   2
P     0.0   0.0  0.29   6.1 0.47 13.7  48.5  454.0   79.0   0.922  2.03  20.9   14.9   2
-----------------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #3 : BASE CATALYST  UPSTREAM       NATURAL GAS
-------------------------------------------------------------------------------------
Mode Power  Vel. Fuel  Air   CO    CO2  NOx   RHC    CH4     O2     H/C  AFmas  AFem Repeats
      kW   km/h  g/s   g/s   %      %   ppm   ppm    ppm      %
-------------------------------------------------------------------------------------
A     0.0   0.0 0.00   0.0 0.00  0.0   0.0    0.0     0.0  0.000  0.00   0.0   0.0   0
B    12.8  51.7 1.66  27.3 0.51 11.0 471.6   53.2   677.0  0.851  3.73  16.4  17.2   2
C    25.2  88.8 3.16  50.1 0.46 11.1 571.9   53.5   502.0  0.591  3.80  15.8  17.2   2
D     7.6  47.9 1.33  20.9 0.72 10.6 160.3   36.2   775.0  1.113  3.79  15.7  17.4   3
E     4.0  46.2 1.07  17.5 0.68 10.6  99.9   48.0   822.0  1.161  3.82  16.5  17.5   3
F    22.9  45.9 2.09  33.1 0.46 11.0 635.1   35.0   652.0  0.743  3.84  15.9  17.3   3
G    16.1  84.8 2.45  39.6 0.55 11.1 380.0   43.0   418.0  0.644  3.76  16.2  17.1   2
H    32.5  87.1 3.44  54.6 0.53 11.2 592.4   52.2   518.0  0.502  3.75  15.9  17.0   3
I    23.0  72.2 2.47  40.2 0.45 11.0 527.2   44.3   538.0  0.681  3.86  16.3  17.3   3
J    15.2  74.6 2.20  35.0 0.47 11.2 424.3   56.1   462.0  0.649  3.70  15.9  17.1   3
K     8.2  70.9 1.75  27.8 0.55 11.1 232.3   46.5   464.0  0.760  3.70  15.9  17.1   3
L    36.3  58.7 3.41  54.7 0.45 11.3 762.9   55.7   540.0  0.664  3.62  16.0  17.0   3
M    14.3  30.8 1.67  26.2 0.47 11.0 515.4   48.0   611.0  1.075  3.69  15.7  17.4   2
N    24.5  31.4 2.51  39.4 0.45 11.2 689.1   41.6   642.0  0.564  3.75  15.7  17.1   3
O     7.2  32.3 1.05  17.5 0.65 10.9 231.1   54.6   879.0  1.110  3.66  16.7  17.3   3
P     0.0   0.0 0.39   7.5 0.10  8.4  15.8   20.3  4919.0  6.250  3.54  19.3  22.0   3
-------------------------------------------------------------------------------------
```

ANALYSIS.BAS: OCN/MDC - JAN 22 94: RAW EXPERIMENTAL RESULTS

TRUCK #3 : ENGLEHARD CATALYST UPSTREAM GASOLINE

Mode	Power kW	Vel. km/h	Fuel g/s	Air g/s	CO %	CO2 %	NOx ppm	RHC ppm	CH4 ppm	O2 %	H/C	AFmas	AFem	Repeats
A	0.0	0.0	0.00	0.0	0.00	0.0	0.0	0.0	0.0	0.000	0.00	0.0	0.0	0
B	13.2	52.6	1.86	28.1	0.58	13.4	456.1	260.9	0.0	0.614	2.29	15.1	15.2	3
C	23.8	90.3	3.21	49.7	0.36	13.6	702.6	231.7	0.0	0.507	2.32	15.5	15.3	2
D	7.9	49.0	1.46	22.4	0.50	13.2	214.0	282.4	0.0	0.703	2.41	15.4	15.4	3
E	4.0	46.2	1.20	18.5	0.42	13.2	128.7	354.3	0.0	0.607	2.46	15.5	15.4	2
F	23.7	43.8	2.21	34.1	0.40	13.3	596.7	256.9	0.0	0.561	2.41	15.4	15.4	2
G	15.8	86.3	2.60	40.4	0.34	13.5	463.5	220.3	0.0	0.527	2.37	15.5	15.3	2
H	32.3	86.0	3.63	54.9	0.71	12.9	694.1	205.3	0.0	0.753	2.43	15.1	15.5	2
I	23.1	71.4	2.60	40.6	0.39	13.1	631.2	239.9	0.0	0.462	2.56	15.6	15.5	2
J	15.4	76.1	2.32	35.8	0.34	13.1	388.3	211.9	0.0	0.534	2.56	15.4	15.6	3
K	8.1	74.3	1.88	29.5	0.49	13.1	231.1	228.2	0.0	0.534	2.54	15.7	15.5	2
L	36.3	58.7	3.28	51.3	0.52	13.2	756.3	251.8	0.0	0.575	2.39	15.6	15.3	3
M	14.0	31.0	1.68	25.3	0.40	13.0	474.3	279.1	0.0	0.565	2.56	15.0	15.6	3
N	15.6	31.4	1.90	28.7	0.37	13.1	437.2	304.6	0.0	0.643	2.53	15.2	15.6	4
O	7.4	32.9	1.17	18.0	0.36	12.9	206.4	359.7	0.0	0.708	2.58	15.5	15.6	2
P	0.0	0.0	0.36	6.4	0.41	12.9	58.6	561.4	0.0	0.925	2.52	18.1	15.5	3

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #3 : ENGLEHARD CATALYST  UPSTREAM        NATURAL GAS
-----------------------------------------------------------------------------------------------
Mode Power  Vel.  Fuel   Air   CO    CO2  NOx    RHC     CH4      O2     H/C   AFmas  AFem Repeats
      kW   km/h   g/s    g/s   %      %   ppm    ppm     ppm       %
-----------------------------------------------------------------------------------------------
A      0.0   0.0  0.00    0.0 0.00  0.0    0.0     0.0     0.0   0.000  0.00   0.0    0.0   0
B     13.2  52.4  1.81   27.6 0.43 11.1 274.1     0.0   820.0   0.900  3.71  15.5   17.4   3
C     24.0  89.2  2.91   49.8 0.57 11.3 440.8     0.0   577.0   0.522  3.63  17.1   16.9   2
D      7.6  48.9  1.26   21.5 0.82 10.6  82.0    36.1  1234.0   1.016  3.78  17.1   17.2   2
E      4.2  46.4  1.06   18.0 0.70 10.6  56.5    23.4  1628.0   1.243  3.72  17.1   17.3   3
F     22.6  43.4  1.90   32.5 0.44 11.2 423.5    53.4   701.0   0.759  3.64  17.1   17.1   3
G     16.6  87.8  2.44   41.7 0.57 11.1 300.9   113.9   389.0   0.656  3.65  17.1   16.9   2
H     32.0  86.2  3.15   53.8 0.46 11.4 492.1    74.4   462.0   0.534  3.59  17.1   16.8   3
I     23.1  72.0  2.39   40.9 0.81 10.9 378.5    60.5   635.0   0.680  3.70  17.1   16.9   2
J     15.4  75.9  2.08   35.5 0.53 10.9 248.2    65.8   473.0   0.859  3.78  17.1   17.3   3
K      8.1  72.4  1.67   28.5 0.56 10.8 120.3    57.3   542.0   0.898  3.86  17.1   17.4   3
L     37.3  59.0  3.29   56.3 0.49 11.3 625.2    65.8   606.0   0.555  3.65  17.1   16.9   3
M     14.4  31.2  1.52   26.0 0.32 10.9 308.4    50.9   761.0   0.895  3.88  17.1   17.5   3
N     24.1  30.4  2.36   40.4 0.88 10.7 426.7    55.5   743.0   0.672  3.77  17.1   17.0   3
O      7.8  35.0  1.11   18.9 0.84 10.3 124.5     7.4  1920.0   1.251  3.84  17.1   17.4   2
P      0.0   0.0  0.55    9.4 0.14  7.3  60.8     0.0  3277.0   6.137  4.83  17.1   24.1   2
-----------------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #4 : CONVERTED  UPSTREAM       GASOLINE
----------------------------------------------------------------------------------------------
Mode Power  Vel. Fuel   Air   CO    CO2  NOx    RHC    CH4     O2      H/C   AFmas   AFem Repeats
      kW   km/h  g/s    g/s   %      %   ppm    ppm    ppm      %
----------------------------------------------------------------------------------------------
A      0.0   0.0  0.00   0.0 0.00  0.0    0.0    0.0    0.0   0.000  0.00   0.0    0.0    0
B     13.3  52.1  1.76  25.6 0.68 14.5 582.0  233.3    0.0   0.816  1.66  14.5   14.4    3
C     24.7  88.7  3.34  44.9 0.49 14.9 796.7  208.3    0.0   0.503  1.66  13.4   14.3    2
D      7.5  48.2  1.32  19.7 0.39 14.9 315.9  246.9    0.0   0.634  1.64  15.0   14.4    3
E      4.4  47.0  1.20  17.1 0.50 14.7 555.5  229.0    0.0   0.691  1.66  14.3   14.4    2
F     22.6  45.1  2.14  30.3 0.63 14.7 783.9  241.8    0.0   0.702  1.64  14.2   14.3    2
G     15.6  88.5  2.66  37.5 0.54 13.9 573.9  185.4    0.0   0.571  2.08  14.1   14.9    2
H     32.3  86.7  3.54  49.1 0.41 15.0 840.5  197.5    0.0   0.496  1.64  13.9   14.3    3
I     23.2  70.9  2.63  36.9 0.59 14.8 703.2  221.6    0.0   0.635  1.64  14.0   14.3    2
J     15.1  74.8  2.30  31.9 0.44 14.9 524.2  189.2    0.0   0.481  1.66  13.9   14.3    3
K      7.8  72.4  1.88  26.0 0.55 14.9 696.4  131.6    0.0   0.455  1.67  13.9   14.3    2
L     35.4  57.7  3.20  44.7 0.44 14.8 867.1  225.3    0.0   0.533  1.68  14.0   14.4    3
M     14.2  30.2  1.72  23.6 0.57 14.8 684.4  276.0    0.0   0.543  1.67  13.7   14.3    2
N     23.9  30.7  2.52  36.2 0.43 14.9 833.9  225.6    0.0   0.481  1.67  14.4   14.3    3
O      7.3  33.6  1.19  16.4 0.45 14.8 352.6  299.6    0.0   0.624  1.67  13.8   14.3    2
P      0.0   0.0  0.44   5.9 0.34 14.8  59.0  507.4    0.0   0.761  1.64  13.6   14.3    3
----------------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS:  OCN/MDC - JAN 22 94:  RAW EXPERIMENTAL RESULTS
TRUCK #4 : CONVERTED  UPSTREAM       NATURAL GAS
-----------------------------------------------------------------------------------------------
Mode Power  Vel. Fuel   Air   CO    CO2  NOx   RHC    CH4      O2     H/C   AFmas  AFem Repeats
      kW   km/h  g/s   g/s    %      %   ppm   ppm    ppm      %
-----------------------------------------------------------------------------------------------
A     0.0   0.0 0.00   0.0 0.00  0.0   0.0    0.0     0.0   0.000  0.00   0.0    0.0   0
B    13.2  51.6 1.65  26.7 0.03 11.1 429.4   57.3   300.0   1.484  3.55  16.2   17.7   3
C    25.1  90.0 3.21  47.6 0.50 11.4 468.2   62.9   375.0   0.349  3.57  14.8   16.7   2
D     8.0  49.6 1.35  21.1 0.05 11.5 209.4   48.7   358.0   1.035  3.47  15.7   17.2   3
E     4.0  46.2 1.14  17.3 0.05 11.3 109.6   46.2   469.0   1.599  3.40  15.2   17.6   2
F    23.5  45.5 2.49  39.1 0.04 11.3 453.0   60.2   169.0   1.021  3.68  15.7   17.5   3
G    16.7  87.3 2.57  40.3 0.23 11.4 416.3   71.3   165.0   0.462  3.76  15.7   17.1   2
H    32.0  86.9 3.47  52.0 0.37 11.3 449.6   77.3   138.0   0.412  3.77  15.0   17.0   3
I    22.9  69.4 2.46  38.8 0.06 11.3 498.3   53.1   281.0   0.848  3.76  15.8   17.5   2
J    15.4  76.5 2.18  35.4 0.05 11.0 331.5   67.7     0.0   1.504  3.75  16.2   18.0   2
K     7.6  76.2 1.73  29.4 0.05 10.7 167.9   62.3     0.0   2.071  3.74  17.0   18.5   2
L    40.0  63.5 4.18  63.0 0.35 10.8 498.0   88.5     0.0   0.340  4.20  15.1   17.5   2
M    14.1  30.1 1.60  25.8 0.04 10.6 327.9   80.5   160.0   1.394  4.09  16.1   18.3   3
N    23.6  29.8 2.79  44.3 0.12 11.2 403.8   71.4     0.0   0.814  3.83  15.9   17.5   2
O     7.8  33.3 1.08  18.0 0.05 11.1 219.5   47.9   520.0   1.088  3.82  16.7   17.7   2
P     0.0   0.0 0.35   6.2 0.25 11.2  41.0    3.4  1349.0   0.623  3.84  18.2   17.2   3
-----------------------------------------------------------------------------------------------
```

```
ANALYSIS.BAS : OCN/MDC - JAN 22 94
HIGH POWER MODE TEST
RAW EXPERIMENTAL DATA
GASOLINE
TRUCK #1  (CONVERTED)

---------------------------------------------
Mode Eng    Eng    Dyno   Dyno   Dyno    A/F
     Speed  Torque Torque Power  Speed
     (rpm)  (N.m)  (N.m)  (kW)   (rpm)
---------------------------------------------
QD0  2187    303   1191    69     557   12.3

QD1  2168    298   1169    68     553   12.6

QD2  2210    305   1178    71     573   12.6

QD3  2199    300   1145    69     576   12.5

QD4  3180    293    964    98     978   12.2

QD5  3714    275    871   107    1171   12.1

QD6  3675    275    872   106    1159   12.2

QD7  3880    260    824   105    1224   12.2

QD8  2356    302   1064    75     669   13.0

QD9  2656    306   1031    85     789   12.7

RD0  2173    303   1201    69     549   12.8

RD1  2488    308   1061    80     723   13.0

RD2  2336    303   1072    74     659   12.2

RD3  2360    302   1056    75     674   13.1

RD4  2189    303   1198    69     553   13.4

RD5  2179    303   1201    69     549   12.6

---------------------------------------------
```

```
ANALYSIS.BAS : OCN/MDC - JAN 22 94
HIGH POWER MODE TEST
RAW EXPERIMENTAL DATA
NATURAL GAS
TRUCK #1  (NO SPARK ADVANCE):

----------------------------------------------
Mode Eng    Eng    Dyno   Dyno   Dyno     A/F
     Speed  Torque Torque Power  Speed
     (rpm)  (N.m)  (N.m)  (kW)   (rpm)
----------------------------------------------
QD0  1932    235    931    48     488    16.0

QD1  1988    239    913    50     520    15.2

QD2  3827    215    687    86    1198    16.7

QD3  2764    247    808    71     845    15.9

QD4  2981    246    794    77     925    16.3

QD5  2986    245    787    76     927    16.8

QD6  2067    237    841    51     582    17.2

QD7  2682    248    812    70     819    16.7

QD8  2717    248    809    70     832    16.0

QD9  1991    232    862    48     536    16.9

RD0  2060    235    842    51     576    15.2

RD1  3145    240    768    79     983    16.6

RD2  3139    239    766    79     980    16.3

RD3  2859    229    690    68     892    16.1

RD4  3465    235    749    85    1088    16.5

RD5  3799    216    688    86    1195    16.2

RD6  4127    195    620    84    1303    94.0

RD7  4294    186    586    84    1361    89.7

----------------------------------------------
```

```
ANALYSIS.BAS : OCN/MDC - JAN 22 94
HIGH POWER MODE TEST
RAW EXPERIMENTAL DATA
TRUCK #1  (MIXER ADJUSTED)

--------------------------------------------
Mode Eng    Eng    Dyno   Dyno   Dyno    A/F
     Speed  Torque Torque Power  Speed
     (rpm)  (N.m)  (N.m)  (kW)   (rpm)
--------------------------------------------
QD0  2859    244    793    73     881   12.9

QD1  3032    240    774    76     940   13.6

QD2  2355    234    787    58     700   13.1

QD3  3986    209    668    87    1251   15.1

QD4  3414    239    761    85    1070   14.2

QD5  3941    210    669    87    1239   15.1

QD6  2025    234    866    50     548   14.0

QD7  1986    235    882    49     529   13.3

QD8  1925    233    929    47     482   13.8

QD9  2355    234    787    58     700   13.1

--------------------------------------------
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```
ANALYSIS.BAS : OCN/MDC - JAN 22 94
HIGH POWER MODE TEST
RAW EXPERIMENTAL DATA
AUGUST 20, 1992
TRUCK #1   (MIXR ADJUSTED)

---------------------------------------------
Mode Eng    Eng    Dyno   Dyno   Dyno    A/F
     Speed  Torque Torque Power  Speed
     (rpm)  (N.m)  (N.m)  (kW)   (rpm)
---------------------------------------------
QD0  2859    244    793    73     881    12.9

QD1  3032    240    774    76     940    13.6

QD2  2355    234    787    58     700    13.1

QD3  3986    209    668    87    1251    15.1

QD4  3414    239    761    85    1070    14.2

QD5  3941    210    669    87    1239    15.1

QD6  2025    234    866    50     548    14.0

QD7  1986    235    882    49     529    13.3

QD8  1925    233    929    47     482    13.8

QD9  2355    234    787    58     700    13.1

---------------------------------------------
```

```
ANALYSIS.BAS : OCN/MDC - JAN 22 94
HIGH POWER MODE TEST
RAW EXPERIMENTAL DATA
NATURAL GAS
TRUCK #1  (SPARK ADVANCED)

--------------------------------------------------
Mode Eng    Eng    Dyno   Dyno   Dyno    A/F
     Speed  Torque Torque Power  Speed
     (rpm)  (N.m)  (N.m)  (kW)   (rpm)
--------------------------------------------------
QD0  2114    262    956    58     579    18.7

QD1  2036    271   1076    58     512    17.7

QD2  3596    186    521    70    1147    18.2

QD3  2164    274    995    62     597    17.5

QD4  3608    263    838    99    1133    17.5

QD5  3553    267    851    99    1116    17.6

QD6  2084    276   1076    60     535    17.4

QD7  3184    281    901    94     992    17.2

QD8  2104    276   1053    61     551    17.6

QD9  2063    277   1098    60     520    17.5

RD0  2060    277   1106    60     515    17.4

RD1  4124    226    714    98    1308    17.8

RD2  3919    243    776   100    1229    17.7

--------------------------------------------------
```

```
ANALYSIS.BAS : OCN/MDC - JAN 22 94
HIGH POWER MODE TEST
RAW EXPERIMENTAL DATA
NATURAL GAS
TRUCK #2  (CONVERTED)

---------------------------------------------
Mode Eng    Eng    Dyno   Dyno   Dyno    A/F
     Speed  Torque Torque Power  Speed
     (rpm)  (N.m)  (N.m)  (kW)   (rpm)
---------------------------------------------
QD0  3301    306    992   106    1018   11.4

QD1  2261    313   1215    74     582   12.9

QD2  2246    315   1239    74     571   12.6

QD3  2319    314   1166    76     625   12.1

QD4  3376    308    994   109    1047   11.0

QD5  3055    315   1033   101     933   11.0

QD6  3844    275    871   111    1212   10.9

QD7  3832    276    876   111    1208   11.0

QD8  4187    247    786   108    1317   10.7

QD9  4066    257    815   109    1282   10.8

RD0  3289    310   1001   107    1017   11.0

RD1  2378    316   1135    79     662   12.1

RD2  2981    318   1048    99     905   11.3

RD3  2253    316   1261    75     564   12.6

---------------------------------------------
```

```
ANALYSIS.BAS : OCN/MDC - JAN 22 94
HIGH POWER MODE TEST
RAW EXPERIMENTAL DATA
GASOLINE
TRUCK #3  (BASE CATALYST)

-----------------------------------------------------
Mode Eng     Eng    Dyno   Dyno   Dyno      A/F
     Speed   Torque Torque Power  Speed
     (rpm)   (N.m)  (N.m)  (kW)   (rpm)
-----------------------------------------------------
QD0  3663     291    931   112    1144      11.2

QD1  2334     316   1161    77     635      12.5

QD2  2279     317   1221    76     592      12.5

QD3  2346     318   1161    78     642      12.2

QD4  2443     316   1111    81     695      12.3

QD5  3432     311   1005   112    1062      11.5

QD6  3031     320   1055   101     919      11.9

QD7  3372     314   1015   111    1043      11.7

QD8  3459     311   1001   113    1073      11.4

QD9  3449     311   1003   112    1070      11.5

RD0  3532     308    989   114    1098      11.4

RD1  3534     307    986   113    1100      11.4

RD2  3793     289    926   115    1184      11.6

RD3  3831     286    917   115    1196      11.3

RD4  3911     279    897   114    1215      11.4

RD5  3991     273    877   114    1241      11.4

RD6  4095     266    851   114    1280      11.5

RD7  4093     264    842   113    1284      11.3

RD8  2967     322   1066   100     896      12.0

RD9  2721     323   1095    92     804      11.8

SD0  2234     318   1261    74     564      12.6
-----------------------------------------------------
```

ANALYSIS.BAS : OCN/MDC - JAN 22 94
HIGH POWER MODE TEST
RAW EXPERIMENTAL DATA
NATURAL GAS
TRUCK #3 (BASE CATALYST)

Mode	Eng Speed (rpm)	Eng Torque (N.m)	Dyno Torque (N.m)	Dyno Power (kW)	Dyno Speed (rpm)	A/F
QD0	2046	265	1044	57	518	15.9
QD1	2639	273	914	75	787	15.4
QD2	2087	266	1016	58	547	16.6
QD3	2090	266	1024	58	543	15.6
QD4	2111	265	989	59	566	16.4
QD5	2158	261	936	59	603	16.1
QD6	2917	261	852	80	893	15.2
QD7	2617	267	893	73	783	15.7
QD8	2761	263	868	76	837	15.4
QD9	2580	271	911	73	767	16.3
RD0	2938	255	833	79	900	15.9
RD1	2973	255	830	79	913	16.1
RD2	3125	244	787	80	968	15.8
RD3	3349	238	764	83	1042	15.5
RD4	3539	223	719	83	1097	16.1
RD5	3606	223	718	84	1119	16.1
RD6	3662	218	702	84	1139	17.5
RD7	4030	208	661	88	1268	17.3
RD8	3643	224	721	85	1131	17.5
RD9	3952	216	691	90	1239	17.5
SD0	4062	208	663	88	1274	7.4

```
ANALYSIS.BAS : OCN/MDC - JAN 22 94
HIGH POWER MODE TEST
RAW EXPERIMENTAL DATA
GASOLINE
TRUCK #4

----------------------------------------------------
Mode Eng    Eng    Dyno   Dyno  Dyno       A/F
     Speed  Torque Torque Power Speed
     (rpm)  (N.m)  (N.m)  (kW)  (rpm)
----------------------------------------------------
QD0  1638    248    614    42     405     11.4

QD1  2219    307   1191    71     572     12.0

QD2  2315    309   1122    75     638     11.6

QD3  3289    312   1006   107    1020     10.5

QD4  3203    315   1019   106     991     10.8

QD5  2347    308   1098    76     660     11.4

QD6  3390    310    995   110    1056     10.5

QD7  3449    308    986   111    1077     10.5

QD8  3690    293    932   113    1159     10.5

QD9  3643    296    942   113    1143     10.6

RD0  3706    293    933   114    1164     10.3

RD1  3802    287    909   114    1201     10.4

RD2  3868    278    881   112    1219     10.1

RD3  3942    272    861   112    1247      9.9

RD4  3951    271    858   112    1250      9.9

RD5  4001    265    838   111    1266      9.9

RD6  2383    312   1099    78     677     11.0

RD7  2654    316   1068    88     786     10.6

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ANALYSIS.BAS : OCN/MDC - JAN 22 94
HIGH POWER MODE TEST
RAW EXPERIMENTAL DATA
NATURAL GAS
TRUCK #4

Mode	Eng Speed (rpm)	Eng Torque (N.m)	Dyno Torque (N.m)	Dyno Power (kW)	Dyno Speed (rpm)	A/F
QD0	1981	251	991	52	502	15.0
QD1	1857	213	826	41	478	14.1
QD2	2149	251	885	57	610	14.9
QD3	2978	261	843	81	922	14.3
QD4	2119	252	892	56	598	14.6
QD5	3696	243	772	94	1164	14.0
QD6	2897	262	852	80	892	14.2
QD7	2128	250	899	56	593	14.5
QD8	2657	263	867	73	805	14.2
QD9	2304	254	870	61	674	14.4
RD0	2968	233	747	72	925	13.8
RD1	3069	232	743	75	959	14.3
RD2	3311	225	716	78	1039	14.1
RD3	3407	219	696	78	1072	14.2
RD4	3593	212	670	80	1135	14.2
RD5	4145	189	599	82	1307	13.9
RD6	3900	203	645	83	1231	13.9